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PHOTOGRAPHIC OBSERVATIONS OF TIDAL BORES (MASCARETS) IN FRANCE

AUTHOR: Hubert CHANSON

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PHOTOGRAPHIC OBSERVATIONS OF TIDAL BORES (MASCARETS) IN FRANCE

by

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Tidal bores of the Garonne River (Top left), Dordogne River (Top right),

Sélune River (Bottom left) and Sée River (Bottom right) in 2008

Abstract

A tidal bore is a series of waves propagating upstream as the tidal flow turns to rising. It forms during spring tide conditions when the tidal range exceeds 4 to 6 m and the flood tide is confined to a narrow funnelled estuary. The existence is based upon a fragile hydrodynamic balance between the tidal amplitude (*marnage*), the freshwater river flow conditions and the river channel bathymetry, and it is shown that this balance may be easily disturbed by changes in boundary conditions and freshwater inflow. Although the Seine River no longer has its tidal bore, more than of dozen of estuaries are affected by tidal bores in France alone. Herein the writer aims to share his enthusiasm and passion for tidal bores by documenting several tidal bores in France with photographic observations. More than 65 photographs are presented and documented. This technical report is supported by a digital appendix (Appendix B) containing a slide show movie and two sound records available at the University of Queensland institutional open access repository UQeSpace {http://espace.library.uq.edu.au/}. A glossary of technical terms is available after the list of symbols.

Keywords: Tidal bores, Mascarets, Aegir, Pororoca, France, Photographs.

Résumé

Un mascaret est une onde positive de translation, appelée aussi onde de compression ou ressaut en translation, qui se développe avec la marée montante, durant une grande marée, dans un estuaire. Un mascaret peut se produire dans une rivière, quand l'embouchure a un fond plat, et une forme convergente, et le marnage est supérieure à 4 à 6 m. Visuellement, il s'agit d'une onde, ou d'une série d'ondes, se propageant vers l'amont, et c'est une discontinuité de la surface libre, avec un accroissement brutal de la hauteur d'eau. En France, plus d'une douzaine d'estuaires sont sujets à un phénomène de mascaret. Dans ce rapport technique, l'auteur souhaite partager sa passion et son intérêt pour le phénomène du mascaret, en illustrant des mascarets en France avec plus de 65 photographes. Le rapport est complémenté par un appendice digital (App. B), contenant un film de diapositives et des fichiers sons, qui sont disponibles dans le repositoire d'accès gratuit de l'University of Queensland, UQeSpace {http://espace.library.uq.edu.au/}. De plus, un glossaire de termes techniques est fourni après la notation.

Mots-clefs: Mascarets, Tidal bores, Aegir, Pororoca, France, Photographies

TABLE OF CONTENTS

List of symbols

The following symbols are used in this report:

d	water depth (m) measured normal to the invert;
d_1	water depth (m) before the tidal bore arrival;
d_2	water depth (m) immediately after the tidal bore passage;
Fr	Froude number defined as: $Fr = (V + U) / \sqrt{g\,d}$;
Fr_1	bore Froude number defined as: $Fr_1 = (V_1 + U) / \sqrt{g\,d_1}$;
g	gravity acceleration (m/s^2): $g = 9.81$ m/s^2 in France;
t	time (s); Note: all given times are local times, with daylight saving between the last week-end of March and the last week-end of October in France;
U	surge celerity (m/s) for an observer standing on the bank;
V	flow velocity (m/s) positive downstream;
V	river flow velocity (m/s) before the tidal bore arrival, positive downstream;

Subscript

1	initial flow conditions, before the tidal bore arrival;
2	new flow conditions, immediately after the tidal bore passage;

Abbreviations

D/S	downstream;
U/S	upstream.

Glossary

Aggradation: raise in channel bed elevation caused by deposition of sediment material. Another term is accretion.

Bed form: channel bed irregularity that is related to the flow conditions. Characteristic bed forms include ripples, dunes and antidunes.

Bed load: sediment material transported by rolling, sliding and saltation motion along the bed.

Bélanger equation: momentum equation applied across a hydraulic jump in a horizontal channel; the equation was named after Jean-Baptiste BÉLANGER (1841) (CHANSON 2008a).

BERNOULLI: Daniel BERNOULLI (1700-1782) was a Swiss mathematician, physicist and botanist who developed the Bernoulli equation in his "Hydrodynamica, de viribus et motibus fluidorum" textbook (1st draft in 1733, 1st publication in 1738, Strasbourg).

BIDONE: Giorgio BIDONE (1781-1839) was an Italian hydraulician. His experimental investigations on the hydraulic jump were published between 1819 and 1826.

BORDA: Jean-Charles de BORDA (1733-1799) was a French mathematician and military engineer. He achieved the rank of Capitaine de Vaisseau and participated to the U.S. War of Independence with the French Navy. He investigated the flow through orifices and developed the Borda mouthpiece.

BOSSUT: Abbé Charles BOSSUT (1730-1804) was a French ecclesiastic and experimental hydraulician, author of a hydrodynamic treaty (BOSSUT 1772).

BRESSE: Jacques Antoine Charles BRESSE (1822-1883) was a French applied mathematician and hydraulician. He was Professor at the Ecole Nationale Supérieure des Ponts et Chaussées, Paris as the successor of J.B. BELANGER. His contribution to gradually-varied flows in open channel hydraulics is considerable (BRESSE 1860).

BUAT: Comte Pierre Louis George du BUAT (1734-1809) was a French military engineer and hydraulician. He was a friend of Abbé C. BOSSUT. Du BUAT is considered as the pioneer of experimental hydraulics. His textbook (BUAT 1779) was a major contribution to flow resistance in pipes, open channel hydraulics and sediment transport.

CARNOT: Lazare N.M. CARNOT (1753-1823) was a French military engineer, mathematician, general and statesman who played a key-role during the French Revolution.

CAUCHY: Augustin Louis de CAUCHY (1789-1857) was a French engineer from the 'Corps des Ponts-et-Chaussées'. He devoted himself later to mathematics and he taught at Ecole Polytechnique, Paris, and at the Collège de France. He worked with Pierre-Simon LAPLACE and J. Louis LAGRANGE. In fluid mechanics, he contributed greatly to the analysis of wave motion.

CHEZY: Antoine CHEZY (1717-1798) (or Antoine de CHEZY) was a French engineer and member of the French 'Corps des Ponts-et-Chaussées'. He designed canals for the water supply of the city of Paris. In 1768 he proposed a resistance formula for open channel flows called the Chézy equation. In 1798, he became Director of the Ecole Nationale Supérieure des Ponts et Chaussées after teaching there for many years.

Conjugate depth: in open channel flow, another name for sequent depth.

CORIOLIS: Gustave Gaspard CORIOLIS (1792-1843) was a French mathematician and engineer of the 'Corps des Ponts-et-Chaussées' who first described the Coriolis force (i.e. effect of motion on a rotating body).

DARCY: Henri Philibert Gaspard DARCY (1805-1858) was a French civil engineer. He studied at Ecole Polytechnique between 1821 and 1823, and later at the Ecole Nationale Supérieure des Ponts et Chaussées (BROWN 2002). He performed numerous experiments of flow resistance in pipes (DARCY 1858) and in open channels (DARCY and BAZIN 1865), and of seepage flow in porous media (DARCY 1856a,b). He gave his name to the Darcy-Weisbach friction factor and to the Darcy law in porous media.

DUPUIT: Arsène Jules Etienne Juvénal DUPUIT (1804-1866) was a French engineer and economist. His expertise included road construction, economics, statics and hydraulics.

Estuary: water passage where the tide meets a river flow. An estuary may be defined as a region where salt water is diluted with fresh water.

Éteules: French for whelps.

EYTELWEIN: Johann EYTELWEIN (1764-1848) was a German mathematician and engineer.

Fawer jump: undular hydraulic jump.

FROUDE: William FROUDE (1810-1879) was a English naval architect and hydrodynamicist who invented the dynamometer and used it for the testing of model ships in towing tanks. He was assisted by his son Robert Edmund FROUDE who, after the death of his father, continued some of his work, and he used REECH's law of similarity to study the resistance of model ships (FROUDE 1872).

Froude number: The Froude number is proportional to the square root of the ratio of the inertial forces over the weight of fluid. The Froude number is used generally for scaling free surface flows, open channels and hydraulic structures. Although the dimensionless number was named after William FROUDE, several French researchers used it before. BÉLANGER (1828), DUPUIT (1848) and BRESSE (1860) highlighted the significance of the number to differentiate the open channel flow regimes, and BAZIN (1865) confirmed experimentally the findings. Ferdinand REECH introduced the dimensionless number for testing ships and propellers in 1852 (REECH 1852). The number is called the Reech-Froude number in France.

Gradually varied flow: A gradually varied flow is characterised by relatively small changes in velocity and pressure distributions over a short distance (e.g. long waterway).

Hydraulic jump: stationary transition from a rapid, high-velocity flow to a slower fluvial flow motion.

LAGRANGE: Joseph-Louis LAGRANGE (1736-1813) was a French mathematician (CHANSON 2007a). During the 1789 Revolution, he worked on the committee to reform the metric system. He was Professor of mathematics at the École Polytechnique from the start.

Left bank: looking downstream, towards the river mouth, the left bank is on the left.

Mascaret: French for tidal bore (Front page and Fig. i-1).

Mile: See nautical mile.

MONGE: Gaspard MONGE (1746-1818), Comte de Péluse, was a French mathematician who invented descriptive geometry and pioneered the development of analytical geometry. He was a prominent figure during the French Revolution, helping to establish the Système métrique and the École Polytechnique, and being Minister for the Navy and colonies between 1792 and 1793.

Nautical mile: a nautical mile equals 1,852 m.

PITOT: Henri PITOT (1695-1771) was a French mathematician, astronomer and hydraulician. He was a member of the French Académie des Sciences from 1724. He invented the Pitot tube to measure flow velocity in the Seine river (first presentation in 1732 at the Académie des Sciences de Paris).

POISSON: Siméon Denis POISSON (1781-1840) was a French mathematician and scientist. He developed the theory of elasticity, a theory of electricity and a theory of magnetism.

Pororoca: tidal bore of the Amazon river in Brazil.

Positive surge: a positive surge results from a sudden increase in flow depth. It is an abrupt wave front. The unsteady flow conditions may be solved as a quasi-steady flow situation and a positive surge is called a hydraulic jump in translation.

PRONY: Gaspard Clair François Marie Riche de PRONY (1755-1839) was a French mathematician and engineer. He succeeded A. CHEZY as director general of the Ecole Nationale Supérieure des Ponts et Chaussées, Paris during the French Revolution.

Rapidly varied flow: open channel flow characterised by large changes over a short distance (e.g. sharp-crested weir, sluice gate, hydraulic jump).

REECH: Ferdinand REECH (1805-1880) was a French naval instructor who proposed first the Reech-Froude number in 1852 for the testing of model ships and propellers (REECH 1852).

Rapidly varied flow: A rapidly varied flow is characterised by large changes over a short distance (e.g. luice gate, hydraulic jump, tidal bore front).

Right bank: looking downstream, towards the river mouth, the right bank is on the right.

Roller: in hydraulic engineering, a series of large-scale turbulent eddies: e.g., the roller of a hydraulic jump.

Shock waves: in high-velocity, supercritical flows, a flow disturbance (e.g. change of direction, contraction) induces the development of shock waves propagating at the free-surface across the channel. Shock waves are called also lateral shock waves, oblique hydraulic jumps, Mach waves, cross-waves, diagonal jumps.

Sequent depth: In open channel flow, the solution of the momentum equation at a transition between supercritical and subcritical flow gives two flow depths (upstream and downstream flow depths). They are called sequent depths.

Stilling basin: hydraulic structure for dissipating the energy of the flow downstream of a spillway, outlet work, chute or canal structure. In many cases, a hydraulic jump is used as the energy dissipator within the stilling basin.

Supercritical flow: open channel flow characterised by a Froude number greater than unity.

Tidal bore: positive surge of tidal origin developing in an estuary as the tide turns to rising.

Undular hydraulic jump: stationary hydraulic jump characterised by steady free-surface undulations downstream of the jump and by the absence of a formed roller. An undular jump flow is called a Fawer jump in homage to Carlos FAWER's (1937) work.

Weak jump: A weak hydraulic jump is characterised by a marked roller, no free-surface undulation and low energy loss. It is usually observed after the disappearance of undular hydraulic jump with increasing upstream Froude numbers.

Whelps: waves behind the leading edge of the tidal bore front. For an observer standing on the bank, the whelps are the wave trains (incl. secondary waves) seen after the surge front passage.

Tidal bore vocabulary

Language	Positive surge of tidal origin	Local bore names	Undular waves	Chaotic wave motion
English	tidal bore		undulations whelps	
French	*mascaret*	*barre* ou *flot* (Seine) *montant* (Garonne)	*éteules*	*éteules* *ressac*
Portuguese (Brazil)	*pororoca*	*pororoca* (Amazon, Guama, Araguari ...)		
Spanish		*burro* (Colorado)		
Gallic	*aegir* (or *eagre*)			
Malay	*benak*			
Papua	*ibua*	*ibua*		
Bengali (Bangladesh)		*ban*		
India	*bahu*			

Language	Low freshwater inflow conditions	Spring tides	Neap tides	Tidal range
English		spring tides	neap tides	tidal range
French	*étiage*	*grandes marées*	*mortes eaux*	*marnage*

Language	Dam break wave
English	dam break wave
French	*onde de rupture de barrage*
German	*Dammbruchwellen*

1. Introduction

1.1 Presentation

A tidal bore is a series of waves propagating upstream as the tidal flow turns to rising. It forms during spring tide conditions when the tidal range exceeds 4 to 6 m and the flood tide is confined to a narrow funnelled estuary. Herein, the estuarine zone is defined as a water body where the tide meets a river flow. In other words, the estuary corresponds to the river section where mixing of freshwater and seawater occurs. Historically, a tidal bore on the Indus River wiped out the fleet of Alexander the Great in B.C. 325 (or B.C. 326 ?) (ARRIAN 1976, Vol. 2, pp. 156-161, Anabis of Alexander, VI, 19; QUINTUS CURCIUS 1984 p. 233, Book 9, [9]), although the best historically documented tidal bores were those of the Qiantang, Seine and Dordogne Rivers.

The inception and development of a tidal bore are commonly predicted using the method of characteristics and the Saint-Venant equations (BARRE DE SAINT VENANT 1871, LIGGETT 1994, MONTES 1998, CHANSON 2004a). When the sea level increases with time during the early flood tide, the leading edge of the flood tide, called the tidal wave, becomes steeper and steeper, until it forms an abrupt front : i.e., the tidal bore (Fig. 1-1). After the formation of the tidal bore, some energy loss takes place across the bore front that is a discontinuity in water depth and hence a flow singularity. The flow properties immediately upstream and downstream of the surge front must satisfy the continuity and momentum principles (i.e. Bélanger principle) (RAYLEIGH 1908, HENDERSON 1966, LIGGETT 1994, CHANSON 2004a) (Fig. 1-2). Considering a tidal bore in a prismatic channel, the bore is a unsteady flow situation for an observer standing on the bank (Fig. 1-2 Left). Yet the same tidal bore is seen by an observer travelling at the bore speed U as a quasi-steady flow situation called a hydraulic jump in translation (Fig. 1-2 Right). For a rectangular horizontal channel and considering a control volume across the front of the surge travelling at a celerity U (Fig. 1-2 Right), the combination of the continuity and momentum principles yields:

$$\frac{d_2}{d_1} = \frac{1}{2}\left(\sqrt{1+8\,Fr_1^2}-1\right) \tag{1}$$

where d_1 and d_2 are respectively the flow depths immediately before and after the bore passage (Fig. 1-2) and Fr_1 is the surge Froude number defined as:

$$Fr_1 = \frac{V_1 + U}{\sqrt{g\,d_1}} \tag{2}$$

with V_1 the flow velocity before the bore passage positive downstream (i.e. towards the river mouth), U the bore front celerity for an observer standing on the bank and positive upstream, and g the gravity acceleration. Once fully-developed, the bore front propagates as a stable surge. A key feature of tidal bores and positive surges ([1]) is that the wave front absorbs random disturbances on both sides of the front and this makes the tidal bore stable and self-perpetuating (HENDERSON 1966, CHANSON 1999,2004a). As a result, a tidal

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[1] In an open channel, a positive surge is a sudden change in flow that increases the depth (HENDERSON 1966, MONTES 1998), and a tidal bore is a positive surge.

bore can travel over very long distances. For example, during equinoxes, the Amazon River tidal bore (*pororoca*) can travel up to 200 miles upstream of the river mouth (WHEELER 1893).

For surge Froude numbers less than 1.5 to 1.8, the bore front is followed by a train of well-formed, quasi-periodic waves called undulations, secondary waves or whelps. This is the undular (non-breaking) bore (Fig. 1-3A & 2-10). For larger surge Froude numbers, the bore is characterised by a breaking front (Fig. 1-3B & 2-8).

Tidal bores and positive surges were studied by hydraulicians and applied mathematicians for a couple of centuries. Major contributions on positive surges included the works of BAZIN (1865), BARRE DE SAINT VENANT (1871), BOUSSINESQ (1877), then LEMOINE (1948), SERRE (1953), BENJAMIN and LIGHTHILL (1954), PEREGRINE (1966), and more recently HORNUNG et al. (1995) and KOCH and CHANSON (2008a,b).

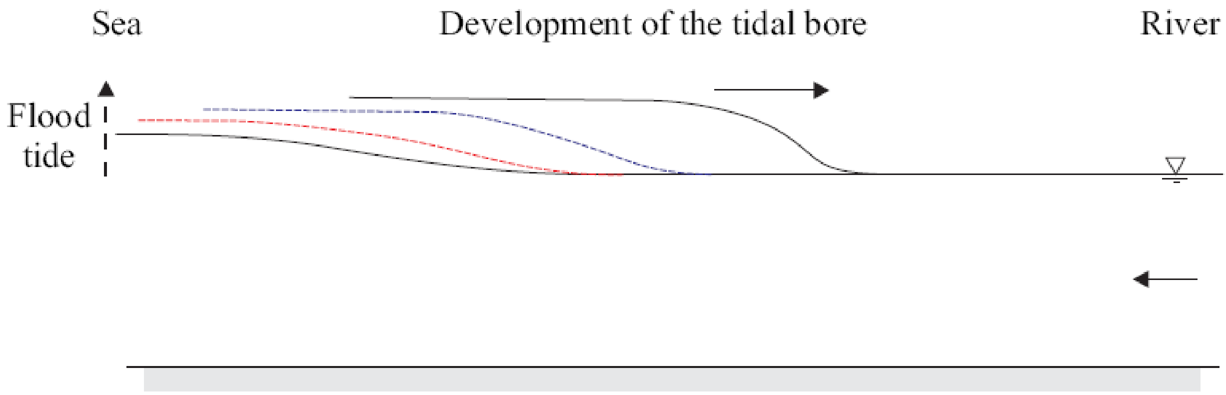


Fig. 1-1 - Sketch of the steepening of the tidal wave into a tidal bore - Free-surface profiles with increasing times

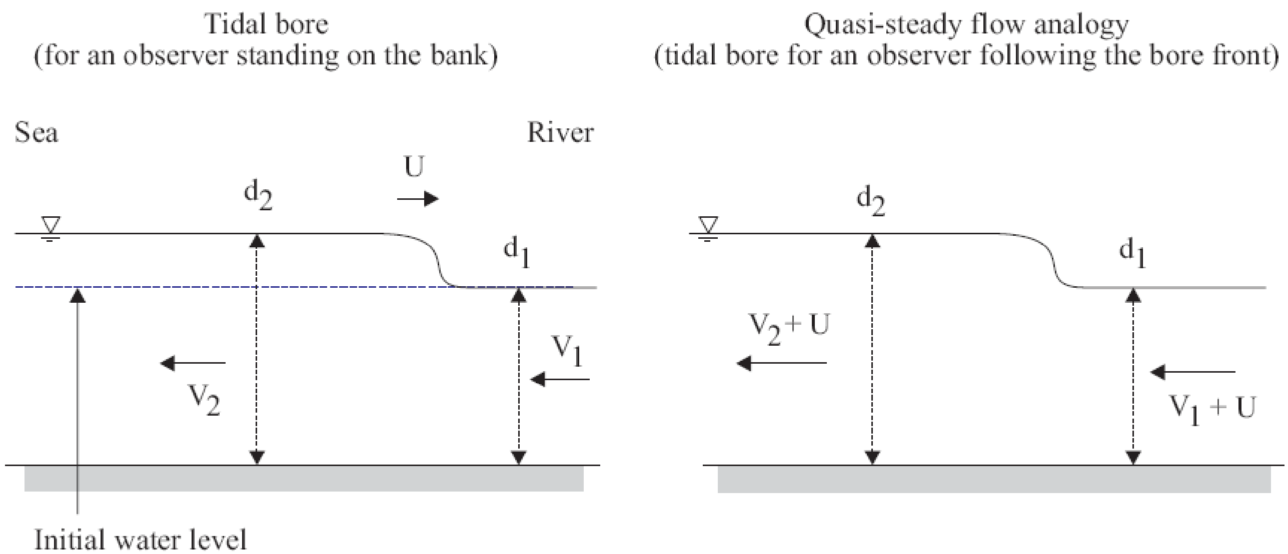
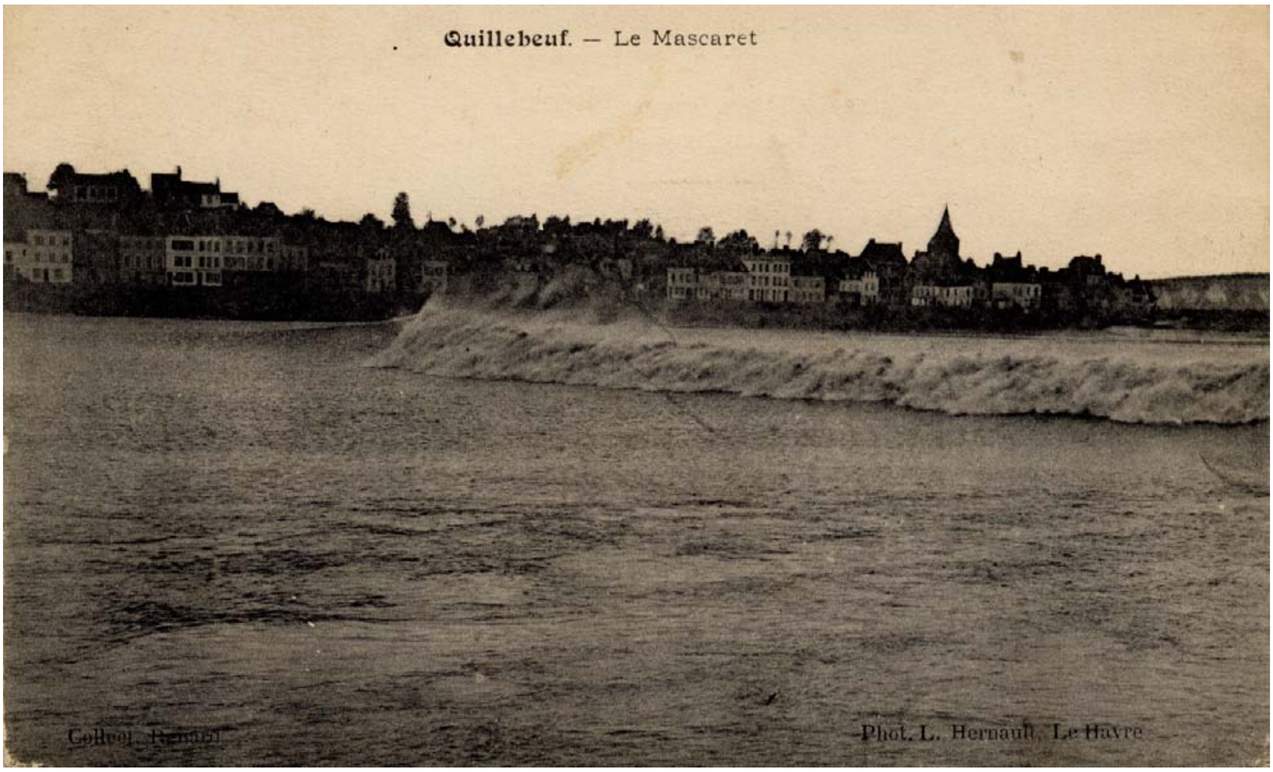


Fig. 1-2 - Definition sketch a tidal bore front propagation and of the quasi-steady flow analogy

(A) Undular tidal bore of the Dordogne River on 27 September 2000 at about 17:00 - This photograph was Earth Science Picture of the Day on 19 December 2001 {http://epod.usra.edu/}



(B) Tidal bore with a breaking front: mascaret of the Seine River at Quilleboeuf (Photo I. HERNAULT, Le Havre from an ancient postcard, Courtesy of J.J. MALANDAIN)

Fig. 1-3 - Photographs of tidal bores

1.2 Impact of tidal bores on estuarine processes

Scientific studies demonstrated that the arrival of the tidal bore is always associated with intense bed material mixing and with upstream advection of suspended material behind the bore front. The effects of tidal bores on sediment processes were studied by CHEN et al. (1990) in the Qiantang River estuary, by TESSIER and TERWINDT (1994) in the Baie du Mont-Saint-Michel, and by GREB and ARCHER (2007) in Alaska, for example. Anecdotal evidences encompassed further BRANNER (1884) in the Amazon (Brazil), KJERFVE and FERREIRA (1993) in the Rio Mearim (Brazil), CHANSON (2001) in the Dordogne River (France), WOLANSKI et al. (2001,2004) in the Ord and Daly Rivers (Australia), CHANSON (2005b,2008b) in the Baie du Mont Saint Michel, and CHANSON (2008b) in the Garonne River. In the Sélune River, the writer observed the formation of a new estuarine channel by the tidal bore on 31 Aug. 2008. The tidal bore cut a channel meander between Pointe du Grouin du Sud and Roche Torin (Fig. 3-6), and the new incision became the main channel by the next morning. The event was followed by intense bed form motion processes and standing waves during the early flood tide flow at Roche Torin on both 31 Aug. and 1 Sept 2008. Also in the Baie du Mont Saint Michel, the tidal bores in the main channels are followed by further tidal bores ([2]) on the sand banks and mudflats. These field observations were supported by experimental measurements of turbulent shear stresses during and after bore front passage (KOCH and CHANSON 2006,2008a,2008b). In undular tidal bores, the sediment suspension is further sustained by strong wave motion of the whelps for relatively long periods after the bore passage, facilitating the upstream advection of the solid matter within the flood flow behind the bore.

Evidences of turbulent mixing induced by tidal bore are plenty. In the Bay of Fundy, RULIFSON and TULL (1999) and MORRIS et al. (2003) studied the longitudinal dispersion of striped bass (*Morone saxatilis*) fish eggs in the tidal bore affected rivers of the Bay of Fundy (Canada). MORRIS et al. (2003) suggested that juvenile striped bass follow the tidal bore front during tidal exchanges and reside in mid-reach freshwater area. Nursery grounds are farther upstream in freshwater habitats and the longitudinal dispersion of the eggs reduce the efficiency of the predators. In the Mersey River (UK) and Rio Mearim (Brazil), salinity measurements during and after tidal bore events showed sharp jumps in salinity and temperature several minutes after the bore passage, with a delay depending upon the sampling site location (DAVIES 1988, KJERFVE and FERREIRA 1993). In the Daly River (Australia), WOLANSKI et al. (2004) recorded a period of very strong turbulence about twenty minutes after the bore passage and lasting for about three minutes.

Tidal bores do cause major damage to river banks and create navigation hazards in tidal bore affected estuaries. More than 220 ships were lost in the Seine River *mascaret* (tidal bore) between 1789 and 1840 in the Quilleboeuf-Villequier section (MALANDAIN 1988). In China, Captain MOORE almost lost his survey ship and two steam cutters when he inadvertently anchored in the Qiantang River estuary in 1888 (MOORE

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[2] The tidal bore advance on sand banks and mud flat is similar to a dam break wave process on dry bed, and it is associated with intense sediment scour and mixing. In Figure 2-9, let us look at the dark brownish waters on the upper left of the photograph. See also Figures 3-10 and 4-9A.

1888, DARWIN 1897). In modern times, the Qiantang River banks were overtopped by the tidal bore and dozens of drownings in the bore flow are reported each year. Other tragic evidences of drownings in tidal bores and "whelps" include numerous human losses in the Colorado River (Mexico), Bamu and Fly Rivers (PNG), and Seine River (France). Related incidents included damage to scientific equipments in the Rio Mearim (Brazil), in the Daly River (Australia), and in the Dee River (UK).

Tidal bores have a significant impact on the eco-systems. Tidal bore affected estuaries are the natural habitat, the feeding zone and breeding grounds of several forms of wildlife. The evidences regroup both scientific and anecdotic observations. In Brazil, the *pororoca* sets organic matters into suspension and the estuarine zone is the feeding grounds of piranhas. In Alaska and in France, several birds of prey are fishing behind the tidal bore front and next to the banks: e.g., bald eagles in Alaska and buzzards in France. Visual observations in Alaska and France showed a number of fish being ejected above the bore roller by the flow turbulence. In Alaska, the eagles catch these fish jumping off and projected upwards above the tidal bore roller. Several large predators feed immediately behind the tidal bore during its upstream progression. These include beluga whales in Alaska (Turnagain inlet), sharks in Queensland (Styx River and Broadsound) and crocodiles in northern Australia. These predators take advantages of the smaller fish that lost their directional awareness in the bore turbulence. In the Dordogne River (France), fishermen profit of the tidal bore to fish shortly before and immediately after the bore passage. Tidal bore estuarine zones are indeed the breeding grounds of several fish species. These include sturgeons and elvers in the Severn River (UK), and striped bass in the Bay of Fundy (Canada). Some animals are also seen playing with the tidal bores. In the Dordogne, Garonne and Severn Rivers, swans were observed surfing the bore front. In a number of occasions, the writer saw himself swans riding the tidal bore front, sometimes before taking off and flying low ahead of the incoming surge (Fig. 2-16).

The noise of the advancing tidal bores is a characteristic feature that affects the animals (see also App. C). At Turnagain, Alaska, a moose tried unsuccessfully to outrun the bore: he was caught and drowned (MOLCHAN and DOUTHIT 1998). In the Baie du Mont Saint Michel, sheep (*moutons de prés salés*) have been outrun and drowned by the tidal bore. In each case, the animals panicked with the deafening noise of the bores and lost their directional senses.

1.3 Fragility of tidal bores

Importantly, the existence of a tidal bore is based upon a fragile hydrodynamic balance between the tidal amplitude (*marnage*), the freshwater river flow conditions (*conditions d'étiage*) and the river channel bathymetry. This balance may be easily disturbed by changes in boundary conditions and freshwater inflow. This is illustrated by the application of the momentum principle to the fully-developed bore front (Fig. 1-2) and the relationship between the flow depths upstream and downstream of the tidal bore front (i.e. Bélanger equation):

$$\frac{d_2}{d_1} = \frac{1}{2}\left(\sqrt{1+8\left(\frac{V_1+U}{\sqrt{g\,d_1}}\right)^2}-1\right) \qquad (1)$$

Despite its simplicity, Equation (1) does explain the occurrence (or disappearance) and strengthening (or weakening) of a tidal bore, as well as its changes in shape and appearance during its propagation. First, a tidal bore does not exist for bore Froude number $Fr_1 = (V_1+U)/\sqrt{g\,d_1}$ less than unity ($Fr_1 < 1$). Tidal bores do not occur during river floods when the initial water depth d_1 is large, and when the tidal range is small (i.e. neap tides).

Second, the strength of a tidal bore is proportional to its Froude number minus unity (Fr_1-1). For $1 < Fr_1 <$ 1.5 to 1.8, the tidal bore is followed by a train of well-defined and quasi-periodic waves called whelps or undulations (Fig. 1-3A). This is the most common type of tidal bores observed on Earth and corresponds to nearly 95% of all tidal bore occurrences ([3]). Breaking bores are observed for $Fr_1 >$ 1.5 to 1.8 (Fig. 1-3B & 3-3). These events are rare and only observed during king tide conditions and low river water levels (*étiages*). Physically the existence of a breaking bore front implies a powerful tidal bore process: e.g., the Seine River mascaret (Fig. 1-3B), the Qiantang River bore during spring tides.

Third, the bore front celerity U is proportional to: $U \propto \sqrt{g\,d_2}$ where d_2 is the water depth immediately behind the bore. In other words, the bore speed is related to the rate of rise of the sea level and to the tidal range. Tidal bores are stronger and advance faster during spring tide conditions. They rarely occur during neap tides.

Fourth, tidal bores are better seen during low river flow periods (*étiages*). For example, the best times to observe tidal bores are spring tides during the month of September for the Dordogne and Garonne Rivers, the months of March and September for the Sée and Sélune Rivers, and the months of September and October during the Moon festival for the Qiantang River in China.

Lastly Equation (1) implies that the bore shape and appearance does change rapidly in response to the estuarine bathymetry. In regions of deeper water (d_1 large), the bore may disappear, while it may strengthen in regions of shallow waters and sand banks (d_1 small). Typical examples of rapid changes in bore shape and appearance are illustrated in Figures 3-6 and 3-7, and Figures 3-11a to 3-11d. Further, in a given river section, the tidal bore may have a breaking bore appearance next to the bank in region of shallow waters, and have an undular shape in a deeper section of the river channel (Fig. 2-11, 3-12 & 3-14).

Man-made interventions led to the disappearance of several bores with often adverse impacts onto the eco-system: e.g., the mascaret of the Seine River (France) no longer exists after extensive training works and dredging, and the Colorado River bore (Mexico) is drastically smaller after dredging. Although the fluvial traffic gained in safety in each case, the ecology of estuarine zones were adversely affected. The tidal bores of the Colorado (Mexico), Couesnon (France) and Petitcodiac (Canada) Rivers almost disappeared after construction of upstream barrage(s). At Petitcodiac, this yielded the elimination of several diadromous fish species, including the American shad, Atlantic salmon, Atlantic tomcod, striped bass and sturgeon (LOCKE et al. 2003). Natural events do also affect tidal bore (CHANSON 2005a). During the 1964 Alaska earthquake

[3] It is estimated that over 400 estuaries are affected by tidal bore processes on Earth. In France alone, tidal bores are experienced in more than a dozen of rivers.

(magnitude 8.5), the inlet floor at Turnagain and Knik Arms subsided by 2.4 m, and smaller bores have been observed since. During a major flood of the Ord River (Australia) in 2001, the flood waters scoured the estuary bed and the bore disappeared completely since. Some natural events may strengthen tidal bores. At Tumagain and Knik Arm inlets, strong and winds opposing the flood tide may strengthen the bore. In Bangladesh, tidal bores were experienced during storm surges when the strong winds developed as the tide turned to rising, causing an increase in the tidal range.

Fig. 1-4 - Barge "Breuil" carrying an Airbus A380 wing section on the Garonne River at Langoiran on 13 September 2008 (Courtesy of Dr Pierre LUBIN) - The barge travelled upstream about 30 minutes after the tidal bore - View from the right bank as the barge passed beneath the Langoiran bridge

The interactions between tidal bores and Humans are complex. Tidal bores can be major tourism attractions. Near Hangzhou, the Qiantang River bore attracts more than 300,000 people each year for the Moon festival while the bore propagation is seen live on television by over 15 millions of television spectators. The tidal bore of the Turnagain Inlet in Alaska is a feature of many organised tours. In the Bay of Fundy, Canada, thrill-seekers ride over the bore in inflatable dinghies (e.g. Shubenacadie River). In Europe, the Dordogne and Severn Rivers are the sites of bore surfing competitions, while, in Brazil, surfing competitions are conducted on the Araguari River. In the early 1960s, the mascaret of the Seine River attracted more than 20,000 people during week-ends. However tidal bores may be dangerous and have a sinister reputation. Dozens of people were killed by flooding caused by the Hangzhou bore: e.g., in June 2000. Bores affect shipping and navigation, as in Papua New Guinea (Fly and Bamu Rivers), Malaysia (Benak at Batang Lupar) and India (Hoogly bore). But sections of the Airbus A380 travel on barges on the Dee and Garonne River estuaries that are both affected by tidal bores (Fig. 1-4). In the Garonne River, the writer saw the barge carrying the aircraft sections between Bordeaux and Langon following the tidal bore by less than 30 minutes to benefit from the strong flood tide current. In the past, the Seine River bore had a sinister reputation (see

below). Similarly the bores of the Petitcodiac River (Bay of Fundy, Canada) and Colorado River (Mexico) were feared (e.g. GORDON 1924). In the Baie du Mont-Saint-Michel, the tidal bores are surprisingly not a major tourist attraction, while tourist walks in the Baie at low tide are rarely warned of the danger of incoming tidal bores.

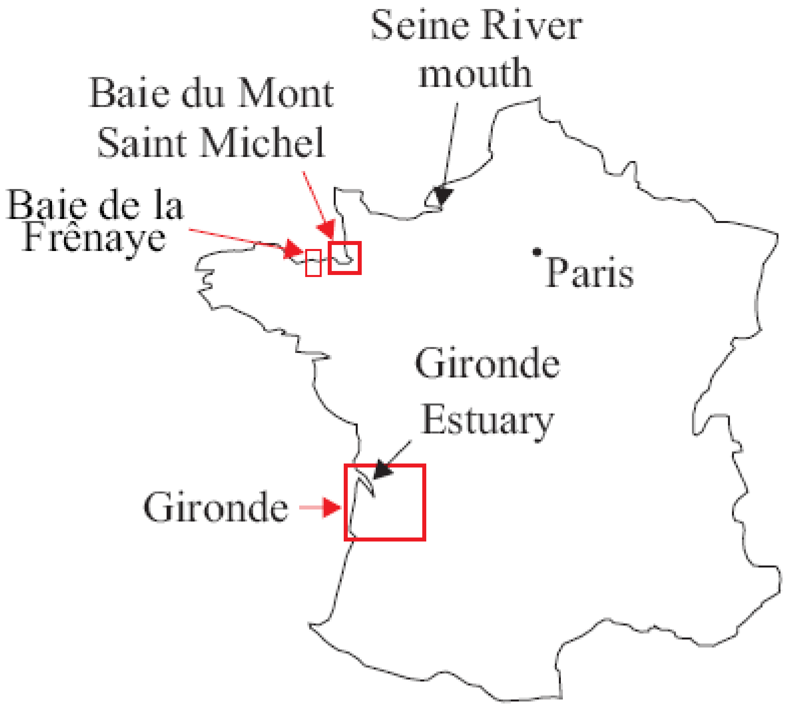

Fig. 1-5 - French regions with tidal bore affected estuaries

1.4 Tidal bores in France

Several tidal bores are observed in French estuaries (Fig. 1-5). One of the most famous tidal bores on Earth was the *mascaret* of the Seine River (Fig. 1-3B & 1-6). The *mascaret* of the Seine River had had a sinister reputation. For example, 112 ships were lost between Quilleboeuf and Villequier from 1789 to 1829; between 1830 and 1851, another 105 ships disappeared between Tancarville and Villequier (MALANDAIN 1988). The height of the bore front could reach up to 7.3 m and the bore front travelled at a celerity of about 2 to 10 m/s (BAZIN 1865, TRICKER 1965). Near the mouth of the river (e.g. at Quilleboeuf), the Seine River mascaret was a breaking bore (Fig. 1-3B). Further upstream the mascaret became an undular bore in the deeper sections of the river while a breaking front was observed near the banks (Fig. 1-6A).

The occurrence of the Seine River *mascaret* was not regular. Observed predominantly during spring tides, its strength was a function of the sand bars near Honfleur, Hode sur la Roque, la Roque sur Nez and le Nez du Quilleboeuf, and the bore could travel up to Rouen nearly 80 km upstream. Following some river training around 1845-1850, the tidal bore disappeared until the end of 1858 when it re-appeared as strong as before. In the 1960s, the mascaret attracted a lot of tourists during the equinox tides, particularly at Caudebec-en-Caux where the bore amplitude was the greatest at the time ([4]). The *mascaret* nearly disappeared following

[4] Interestingly, the Seine River tidal bore was the strongest near Quilleboeuf in the 1800s, at least until 1855

the dredging of the Seine estuary and the new canal de Tancarville, completed in 1963.

Since 1964 the mascaret was occasionally observed, although weaker than in the past: on 28 March 1967 between Sahurs and La Bouille (Paris-Normandie, 29 Mar. 1967), on 7 September and 5 October 1971 at Caudebec-en-Caux (Le-Havre-Presse, 6 Oct. 1971). In 1971, the occurrence of the mascaret was a combination of large tides (coefficients 115-116 in October) and a low river discharge caused by a long drought period.

Today the Seine River tidal bore is still indicated in the nautical instructions of the Port de Rouen, and its reputation remains vivid in the memories of the people of the Baie de Seine, although some myths are untrue. For example, in his memorable poem "A Villequier", Victor Hugo mourned the drowning of his daughter Leopoldine and her husband in the Seine in 1843; but Leopoldine was not drowned in a tidal bore because the day of the accident was during neap tides and there was no tidal bore ([5]).

In the Gironde Estuary, a tidal bore develops during spring tides and continues upstream into the Dordogne and Garonne Rivers (Section 2). Small tidal bores are also observed in their tributaries: e.g., l'Isle River at Libourne. Surfers and kayakers regularly surf the Dordogne and Garonne River tidal bores (Fig. 1-3A, 2-2 to 2-7).

(A) Incoming mascaret at Vieux-Port, near Quilleboeuf (Ancient postcard, Courtesy of J.J. MALANDAIN)

(MALANDAIN 1988). Around 1895, it was the strongest between Saint-Léonard and La Mailleraye.

[5] Further her husband was from a family of ship pilots who knew well the mascaret phenomenon. For more information see {http://www.sequana-normandie.com/}.

(B) Ferry (*Bac*) No. 9 of Caudebec-en Caux facing the *mascaret* in 1958 (Photograph by Alain HUON, courtesy of Nathalie LEMIÈRE) - All small and large boats, as well as ships and ferries, had to leave the wharf to face the *mascaret* in a similar way

Fig. 1-6 - Old photographs of the Seine River tidal bore (*mascaret*)

In the Baie du Mont Saint Michel, several tidal bore processes are experienced in creeks and rivers (TESSIER and TERWINDT 1994, CHANSON 2005b) (Section 3). The largest bores are observed in the Couesnon, Sélune and Sée Rivers.

In Brittany (*Bretagne*), smaller tidal bores are observed in the Baie de la Frênaye, in the Baie de l'Arguenon and at Saint Briac sur Mer (Section 4). In Normandy (*Normandie*), a tidal bore is observed in the Sienne River, North of Granville, and in the Vire River at Carentan. The latter is mentioned in the nautical instructions for the channel between the Baie des Veys and the Carentan harbour. This tidal bore continues beyond Carentan in the Vire River.

1.5 Structure of the report

In this report, the writer aims to share his enthusiasm and passion for tidal bores. Herein he documents with photographic observations several tidal bores in France (Fig. 1-5). He experienced himself all these tidal bore processes. He surfed in kayak the Garonne River tidal bore on 3 September 2008. In dinghy, he followed the tidal bores of the Garonne and Dordogne Rivers for 40 and 27 km respectively on 28 and 30 September 2008. The photographs are presented a river after another one: i.e., Garonne River, then Dordogne River, Isle River, Couesnon River, Sélune River, Sée River ... For each river, the photographs are then shown in chronological order. Unless specified, all photographs were taken by the writer who observed

many tidal bore events between 2000 and 2008. Some maps are shown in Appendix A. The technical report is supported by a digital appendix (Appendix B) containing a slide show movie and some sound tracks available at the University of Queensland institutional open access repository UQeSpace {http://espace.library.uq.edu.au/}. Appendix C discusses the acoustic signature of a tidal bore event.

CHANSON, H. (2008). "Photographic Observations of Tidal Bores (Mascarets) in France." *Hydraulic Model Report No. CH71/08*, Div. of Civil Engineering, The University of Queensland, Brisbane, Australia, 104 pages, 1 movie and 2 audio files (ISBN 9781864999303).

2. Tidal bores in Gironde

One of the best historically documented tidal bores is that of the Dordogne River in south-western France. It was mentioned by Bernard PALISSY (1510-1589) and Nicolas BREMONTIER (1738-1809). BREMONTIER understood in particular that the tidal wave was amplified by the funnel shape and bathymetry of the Gironde Estuary (BREMONTIER 1809). For example, when the tidal range is 4.24 m at Pointe de Grave, at the mouth of Gironde, the tidal range at Bordeaux is 5.56 m ([1]).

The Gironde Estuary in south-western France is formed by the confluence of the Garonne and Dordogne Rivers (App. A). It flows northwest between Bec d'Ambès and the Pointe de Grave for about 72 km and is navigable for oceangoing vessels despite sandbanks and strong tides. The Garonne River has its spring the Spanish central Pyrenees and flows into the Atlantic. It is 575 km long excluding the Gironde Estuary. The catchment area is 56,000 km^2. The Garonne River is affected by the tides from the confluence with Dordogne at Bec d'Ambès up to Castets.

With its spring in the Massif Central, the Dordogne River is 472 km long with a catchment area of 24,000 km^2. The estuarine zone extends from the confluence with the Garonne River up to about Castillon-la-Bataille, and there is some river traffic along the last 112 miles of its course. For example, several centuries ago, the stones from the quarries of Saint Emilion were loaded at Port Saint Martial upstream of Libourne and transported on the Dordogne to the Gironde region downstream.

The tidal bore process spans over several dozens of kilometres in each river. For example, the writer followed the tidal bore of the Dordogne River for 27 km on 30 September 2008 (Fig. 2-7 and 2-8) and that of the Garonne River for over 40 km on 28 September 2008 (Fig. 2-25 and 2-28). He also surfed in kayak the Garonne River on 3 September 2008 (Fig. 2-3 and 2-4).

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[1] Predicted tidal ranges on 1 October 2008.

Fig. 2-1 - Tidal bore of the Garonne River at Podensac on 22 July 2008 at 20:34 - Looking downstream at the incoming tidal bore - The surfer was Frédéric DANEY - File: P1060096.jpg, Shutter speed: 1/500 s

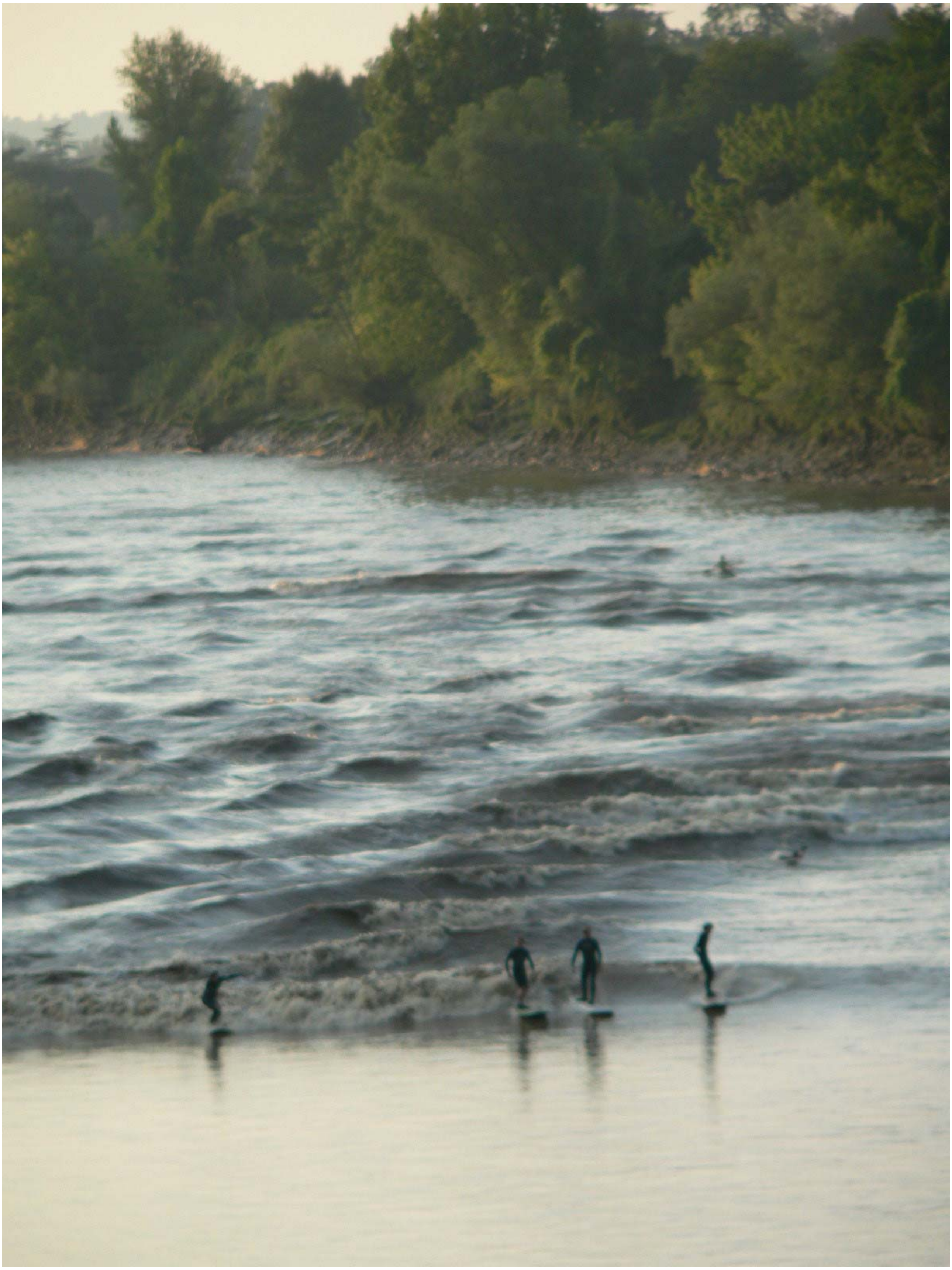

Fig. 2-2 - Tidal bore of the Garonne River at Podensac on 2 September 2008 at 19:49 - Looking downstream at the tidal bore - File: P1070833.jpg, Shutter speed: 1/400 s

Fig. 2-3 - Tidal bore of the Garonne River at Baurech on 3 September 2008 (Photograph by Michel DEYRICH with permission) - Looking downstream at the incoming tidal bore - Hubert CHANSON was on the second kayak from the left with Roger MARCEL -File: P1060757.jpg, Shutter speed: 1/50 s

(A) Roger MARCEL looking behind at the incoming tidal bore breaking next to the left bank (highlight) - File: F1010008.jpg, 800 ASA

(B) Riding the bore front - Pierre LUBIN in the foreground -File: F1010008.jpg, 800ASA

Fig. 2-4 - Surfing the tidal bore of the Garonne River in kayak at Baurech on 3 September 2008 - View from the kayak of Roger MARCEL and Hubert CHANSON

Fig. 2-5 - Tidal bore of the Garonne River at Podensac on 27 September 2008 at 16:48:13 -File: P1080785.jpg, Shutter speed: 1/640 s

Fig. 2-6 - Tidal bore of the Garonne River at Podensac on 27 September 2008 at 16:51:38 -File: P1080820.jpg, Shutter speed: 1/800 s

Fig. 2-7 - Tidal bore of the Garonne River: undular tidal bore upstream of Port de Podensac on 28 September 2008 at 17:34 - Note some breaking next to the left bank (on the left of the photograph) -File: P1090250.jpg, Shutter speed: 1/1,000 s

Fig. 2-8 - Tidal bore of the Garonne River: breaking bore upstream of Cadillac on 28 September 2008 at 17:48 - File: P1090330.jpg, Shutter speed: 1/1,000 s

Fig. 2-9 - Tidal bore of the Garonne River at Podensac on 29 September 2008 at 18:16 - Surfer next to the left bank with the tidal bore rushing on the dry gravel bank (dark brownish waters on the upper left of the photograph) -File: P1090565.jpg, Shutter speed: 1/320 s

Fig. 2-10 - Undular tidal bore of the Garonne River at Arcins on 1 October 2008 at 17:58 - Bore propagation in the "Bras mort" (from right to left) - File: P1100055.jpg, Shutter speed: 1/250 s

Fig. 2-11 - Tidal bore of the Garonne River at Langoiran on 1 October 2008 at sunset (18:48) - File: P1100073.jpg, Shutter speed: 1/800 s

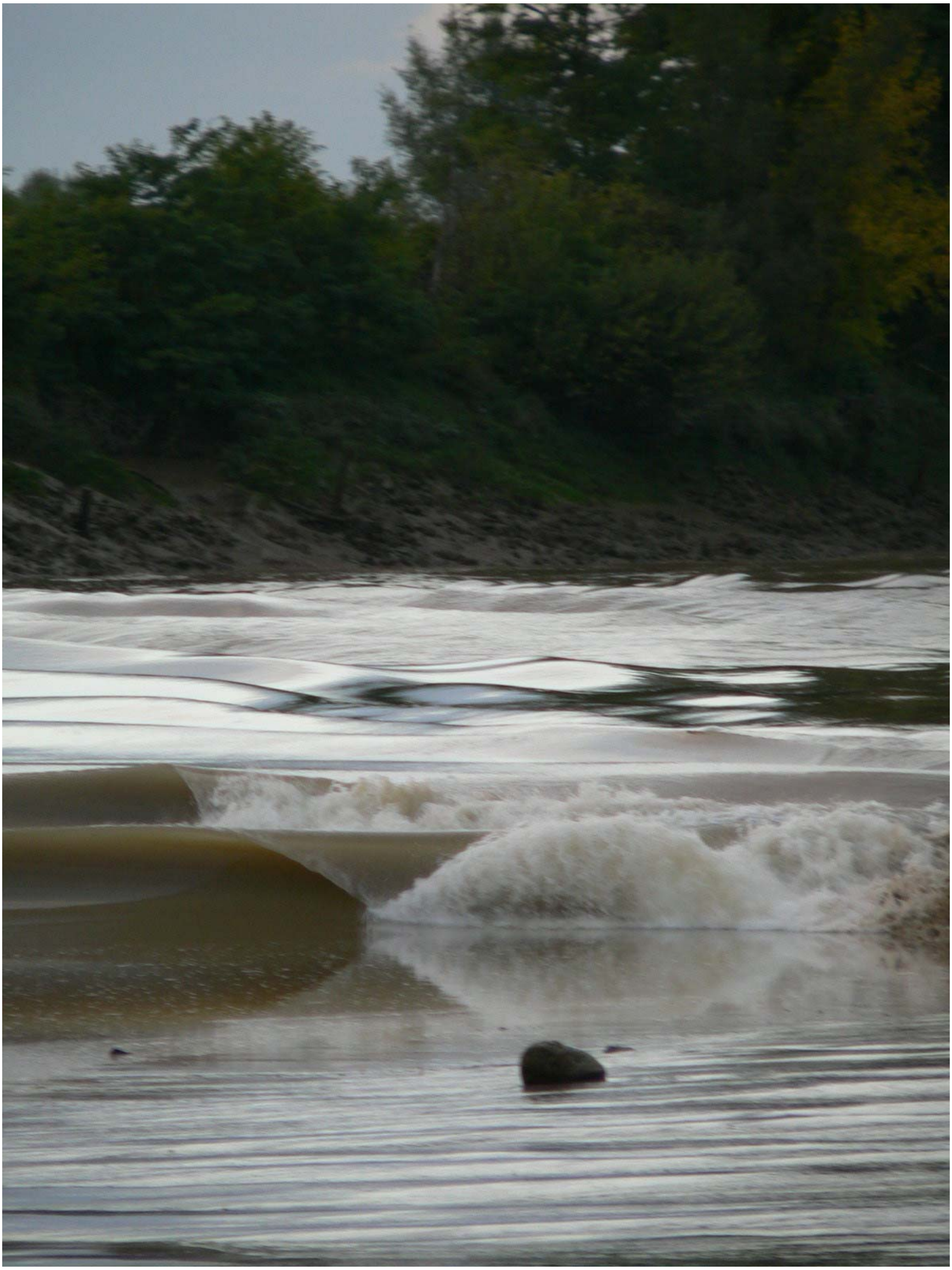

Fig. 2-12 - Tidal bore of the Garonne River at Béguey on 1 October 2008 at 19:25 - Looking downstream at the incoming bore front - File: P1100129.jpg, Shutter speed: 1/80 s

Fig. 2-13 - Tidal bore of the Garonne River at Béguey on 1 October 2008 at 19:26 - Frédéric DANEY and a friend- File: P1100140.jpg, Shutter speed: 1/80 s

Fig. 2-14 - Looking upstream of the disappearing tidal bore of the Dordogne River at Port de Saint Pardon on 21 July 2008 at 07:02 at sunrise - The undular bore had a smooth free-surface profile but close to the banks - File: P1050692.jpg, Shutter speed: 1/200 s

Fig. 2-15 - Turbulence the Dordogne River tidal bore at Port de Saint Pardon on 21 July 2008 at 07:03 at sunrise - Whelps impacting on the boat ramp about 34 seconds after the bore front passage - File: P1050693.jpg, Shutter speed: 1/1,000 s

Fig. 2-16 - Tidal bore of the Dordogne River downstream of Port de Saint Pardon on 22 July 2008 at 07:34:16 at sunrise - Two swans took off in front of the undular bore - File: P1050845.jpg, Shutter speed: 1/640 s

Fig. 2-17 - Tidal bore of the Dordogne River at Port de Saint Pardon on 22 July 2008 at 07:35:23 at sunrise - Undular bore front about to impact the boat ramp - File: P1050857.jpg, Shutter speed: 1/1,000 s

Fig. 2-18 - Undular tidal bore of the Dordogne River at Port de Saint Pardon on 22 July 2008 at 19:37 - The surfer was riding on the third wave - File: P1060027.jpg, Shutter speed: 1/500 s

Fig. 2-19 - Undular tidal bore of the Dordogne River at Port de Saint Pardon on 2 September 2008 at 18:49 - Fabrice COLAS surfing the bore front - File: P1080718.jpg, Shutter speed: 1/800 s

Fig. 2-20 - Undular tidal bore of the Dordogne River at Port de Saint Pardon on 27 September 2008 at 15:49:49- Fabrice COLAS surfing the third wave - Note some wave breaking in the whelps in the background - File: P1080727.jpg, Shutter speed: 1/1,000 s

Fig. 2-21 - Undular tidal bore of the Dordogne River at Port de Saint Pardon on 27 September 2008 at 15:50:04 - Bore front passing in front of the boat ramp - The two kayakers were riding the second wave and Fabrice COLAS was surfing on the third wave - File: P1080739.jpg, Shutter speed: 1/800 s

Fig. 2-22 - Tidal bore of the Dordogne River propagating upstream of Port de Saint Pardon on 27 September 2008 at 15:50:57 - File: P1080760.jpg, Shutter speed: 1/800 s

Fig. 2-23 - Tidal bore of the Dordogne River at Port de Saint Pardon on 29 September 2008 at 17:14 - File: P1090431.jpg, Shutter speed: 1/800 s

Fig. 2-24 - Tidal bore of the Dordogne River at Izon on 30 September 2008 at 17:36 - Fabrice COLAS and Alain MARHIC surfing the second wave next to the left bank - File: P1090803.jpg, Shutter speed: 1/320 s

Fig. 2-25 - Tidal bore of the Isle River at Libourne on 30 September 2008 at 18:23 - Fabrice COLAS and Antony COLAS accelerating with the bore front - File: P1090803.jpg, Shutter speed: 1/320 s

3. Tidal bores in the Baie du Mont Saint Michel

The Baie du Mont-Saint-Michel (France) in the English Channel (*La Manche*) is known for the abbey built on the Mont Saint Michel ([1]), its very large tidal range and fast advancing flood tides (Fig. 3-1). The Baie is an UNESCO World Heritage site since 1979. It is drained by three main rivers: the Couesnon, the Sélune and the Sée (App. A). In the past, the hydrodynamics and sedimentology of the Baie, including the access to the Mont Saint Michel, were mostly affected by the strong flows of the Couesnon and Sélune Rivers. Up to 1863, the Couesnon River was uncontrolled and it flowed past both sides of Mont Saint Michel. A non-submersible digue (dike) to the Mont Saint Michel was completed in 1879 and the river has been flowing West of the Mont since. In 1969, the Couesnon River was further impacted by the construction of a barrage to reduce salt intrusion in the catchment. It will be also affected by major works ([2]) in 2007-2011 with the destruction of part of the digue and of the barrage, and the construction of a new flushing system (LEFEUVRE and BOUCHARD 2002). The Sélune River is 70 km long with a catchment area of 1,010 km^2. It was partially controlled around 1860 after the completion of a digue redirecting the river Northwards. The river was further affected by the completion of two dams (La Roche Qui Boit, 1920; Vezins, 1931) with spillway capacities in excess of 300 m^3/s. Today it constitutes the most significant freshwater inflow into the Baie du Mont Saint Michel. At its mouth between Roche Torin and Pointe du Grouin du Sud, the Sélune River joins the Sée River, and the waters merge at low tides.

During spring tides, the Couesnon, Sélune and Sée Rivers are subjected to tidal bore processes, but the occurrences of bores was seldom documented in the Baie du Mont Saint Michel. LARSONNEUR (1989) mentioned briefly a tidal bore near Pointe du Grouin du Sud propagating at about 2.5 m/s. TESSIER and TERWINDT (1994) discussed the effect of tidal bore on sediment transport downstream of the Sée and Sélune river mouths. CHANSON (2004b,2005b) presented photographic evidences of the tidal bores and discussed their impact on the Baie.

In the Baie du Mont Saint Michel, the tidal bore process develops sometimes outside of the Ile de Tombelaine, and propagates inland along the channels before entering the main river channels. The entire tidal bore phenomenon lasts several hours and spans over more than 15 km.

Fig. 3-1 - Baie du Mont Saint Michel, view from Pointe du Grouin du Sud on 19 September 2008 at low tide

[1] The sanctuary dates back to AD 708 when the mount was called Mont Tombe.

[2] Travaux de Rétablissement du Caractère Maritime du Mont-Saint-Michel.

Fig. 3-2 - Tidal bore of the Couesnon River at Mont Saint Michel on 7 March 2004 at 18:25 - Undular bore at sunset propagating from right to left - File: Couesn25.jpg, Shutter speed: 1/1,000 s

Fig. 3-3 - Tidal bore of the Sélune River at Pontaubault on 7 April 2004 at 09:00 - Breaking bore downstream of the 15th century bridge Pont Aubaud - File: Selun50.jpg, Shutter speed: 1/800 s

Fig. 3-4 - Tidal bore of the Sélune River at Roche Torin on 2 August 2008 at 19:59 at sunset - File: Selun152.jpg, Shutter speed: 1/250 s

Fig. 3-5 - Tidal bore of the Sélune River at Pontaubault on 2 August 2008 at 20:58 - Undular bore approaching the 15th century bridge Pont Aubaud (in background) - Figure 3-5 was taken at 20:58 - File: Selun206.jpg, Shutter speed: 1/250 s

Fig. 3-6 - Tidal bore of the Sélune River at Roche Torin on 31 August 2008 at 19:34:07 - The tidal bore cut a channel meander between Pointe du Grouin du Sud (top left of the photograph) and Roche Torin, and the new incision became the main channel by the next morning - The event was followed by intense bed form motion and standing waves during the early flood tide flow at Roche Torin - File: Selun384.jpg, Shutter speed: 1/250 s

Fig. 3-7 - Tidal bore of the Sélune River at Roche Torin on 31 August 2008 at 19:34:24 - Note the rapid transformation of the bore front between Figures 3-6 and 3-7 taken 17 seconds apart - File: Selun390.jpg, Shutter speed: 1/160 s

Fig. 3-8 - Tidal bore of the Sélune River at Roche Torin on 31 August 2008 at 19:44:42 - File: Selun426.jpg, Shutter speed: 1/80 s

Fig. 3-9 - Small undular tidal bore entering a drainage channel off the Sélune River at Roche Torin on 31 August 2008 at 19:45:42 - The bore passed through the gates (top right) and continued further along the drainage channel (propagation from bottom left to top right) - File: Selun443.jpg, Shutter speed: 1/80 s

Fig. 3-10 - Tidal bore of the Sélune River at Roche Torin on 1 September 2008 at about 08:07 (Photograph by Bernard CHANSON) - In the foreground, the bore front advanced on an initially dry sand bank - File: P9010491.jpg, Shutter speed: 1/250 s

(a) (b) (c) (d)

Fig. 3-11 - Rapid evolution in shape of the tidal bore of the Sélune River at Roche Torin on 1 September 2008 - Figures 3-11a, 3-11b, 3-11c and 3-11d were taken respectively at 08:07:53, 08:12:17, 08:12:49 and 08:12:57 - Files: Selun603.jpg (Shutter speed: 1/320 s), Selun620.jpg (Shutter speed: 1/200 s), Selun628.jpg (Shutter speed: 1/500 s), Selun631.jpg (Shutter speed: 1/640 s)

Fig. 3-12 - Tidal bore of the Sélune River at Roche Torin on 19 September 2008 at 09:30:25 - Note the "wavy" transverse profile of the undular tidal bore - File: Selun765.jpg, Shutter speed: 1/800 s

Fig. 3-13 - Tidal bore of the Sélune River at Roche Torin on 19 September 2008 at 09:32:04 - File: Selun787.jpg, Shutter speed: 1/640 s

Fig. 3-14 - Tidal bore of the Sélune River at Roche Torin on 19 September 2008 at 09:32:50 - File: Selun804.jpg, Shutter speed: 1/1,000 s

Fig. 3-15 - Breaking bore of the Sée-Sélune River system North of Pointe du Grouin du Sud on 14 October 2008 at 18:27:08 - Figure 3-15 was taken just before the tidal bore divided into the Sée and Sélune River channels - File: See076.jpg, Shutter speed: 1/100 s

Fig. 3-16 - Tidal bore of the Sée and Sélune Rivers just North of Pointe du Grouin du Sud on 14 October 2008 at 18:28:21 - The tidal bore was surging into the Sée and Sélune River channels as well as over the sand banks, with the Sélune River channel in the background - File: See093.jpg, Shutter speed: 1/100 s

Fig. 3-17 - Tidal bore of the Sée River just South of Pointe du Grouin du Sud on 14 October 2008 at 18:30:24 (Photograph by Nicole CHANSON) - The tidal bore was entering the Sée River channel and progressed against the steep slope - File: See263b.jpg

Fig. 3-18 - Tidal bore of the Sée and Sélune Rivers just North of Pointe du Grouin du Sud on 19 October 2008 at 09:30:29 - Advancing tidal bore on a sand bank between the main channels - File: See324.jpg, Shutter speed: 1/500 s

Fig. 3-19 - Tidal bore of the Sée and Sélune Rivers at Pointe du Grouin du Sud on 19 October 2008 at 09:30:59 - On that morning the Sée and Sélune Rivers formed a braided channel at Pointe du Grouin du Sud - Note the rocky promontory of Pointe du Grouin du Sud in the foreground and Ile de Tombelaine in the background - File: See333.jpg, Shutter speed: 1/500 s

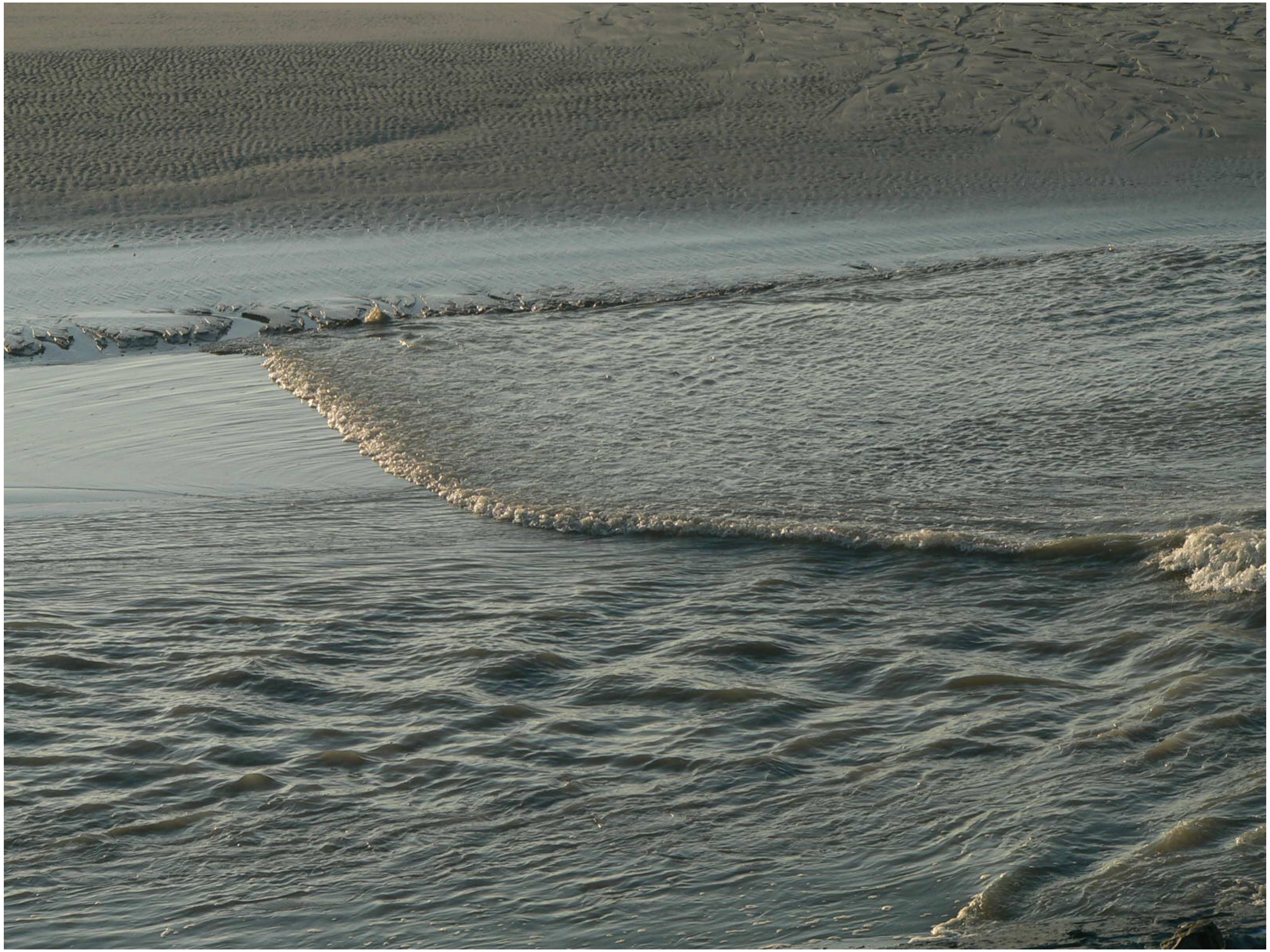

Fig. 3-20 - Tidal bore of the Sée River just South of Pointe du Grouin du Sud on 19 October 2008 at 09:32:40 - The tidal bore was entering the Sée River channel and progressed against the steep slope; some standing waves were visible at the surface of the Sée River (left of the photograph) - Note the differences in bore shape with Figure 3-17 taken 5 days earlier with a larger tidal range - File: See367.jpg, Shutter speed: 1/800 s

Fig. 3-21 - Tidal bore of the Sée River about 250 m away from the Pointe du Grouin du Sud on 19 October 2008 at 09:36:38 - The tidal bore front was divided by a small sand bank - Note the differences in bore shape with Figure 3-20 taken 4 minutes earlier - File: See394.jpg, Shutter speed: 1/640 s

4. Tidal bores in the Baie de la Frênaye and Baie de l'Arguenon

The Baie de la Frênaye and Baie de l'Arguenon are located in Brittany (*Bretagne*) on the English Channel (*La Manche*), between Cap Fréhel and Pointe du Décollé (Saint Lunaire) (App. A). The Baie de la Frênaye itself is located between two historical landmarks: the Pointe de la Latte (Fig. 4-1) and the Pointe de Saint Cast. In the Baie de la Frênaye and Baie de l'Arguenon, there are a number of tidal bore affected creeks. In each case, the tidal bore is small although it can be followed in kayak. These are the Frémur Creek near Fréhel (Côtes d'Armor) in the Baie de la Frênaye, the Arguenon River in the Baie de l'Arguenon, and the nearby Frémur Creek at Saint Briac sur Mer (Ile et Vilaine) (App. A).

In Côtes d'Armor, the Frémur Creek flows into the Baie de la Frênaye at Port-à-la Duc. A *mascaret* develops as the flood tide reached the upper end of the Baie and enters into the creek channel. The tidal bore flows past Port-à-la Duc and continues further upstream.

The Arguenon River is a larger river flowing into the Baie de l'Arguenon at Le Guildo. It is affected by a tidal bore as the flood flow enters the upper end of the Baie and into the river channel. It propagates past the Port du Guildo in front of the ruins of the 15th century castle of Gilles de Bretagne, and reaches the township Plancoët about 30 minutes before high tide.

Located South of Saint Briac sur Mer, the Frémur Creek in Ile et Vilaine is blocked by a tidal mill at La Roche Goude, and its estuarine zone flows to the Baie de la Frênaye between Saint Briac sur Mer and Lancieux. A tidal bore is seen downstream of the tidal mill.

Fig. 4-1 - Fort Lalatte at Pointe de la Latte, marking the entrance of the Baie de la Frênaye, on 15 August 2008 - Built during the 13th and 14th centuries, the castle was restored during the 17th century

(A) Tidal bore passing beneath the 1926 railway bridge at 18:29:34 - File: Fremur045.jpg, Shutter speed: 1/60 s

(B) Breaking bore beneath bridge piers - Figure 4-2B was taken at 18:29:29 - File: Fremur042.jpg, Shutter speed: 1/80 s

Fig. 4-2 - Tidal bore of the Frémur Creek at Port-à-la Duc, Baie de la Frênaye on 15 October 2008

Fig. 4-3 - Tidal bore of the Frémur Creek at Port-à-la Duc, Baie de la Frênaye on 16 October 2008 at 19:11:49 at sunset - Figure 4-3 was taken upstream of the old railway bridge - File: Fremur106.jpg, Shutter speed: 1/80 s

Fig. 4-4 - Tidal bore of the Frémur Creek, Baie de la Frênaye on 16 October 2008 at 19:13:43 at sunset - The bore celerity was about 1.5 m/s - Figure 4-4 was taken further upstream of the bridge of Port-à-la Duc (in background) - File: Fremur112.jpg, Shutter speed: 1/30 s

Fig. 4-5 - Breaking bore of the Frémur Creek, Baie de la Frênaye on 16 October 2008 at 19:14:37 at sunset - The bore celerity was about 1.4 m/s at that location - File: Fremur123.jpg, Shutter speed: 1/30 s

Fig. 4-6 - Tidal bore of the Arguenon River at Les Pierres Sonantes on 15 October 2008 at 17:25:30, with the Baie de l'Arguenon in background - File: Arguen054.jpg, Shutter speed: 1/320 s

Fig. 4-7 - Tidal bore of the Arguenon River at Les Pierres Sonantes, downstream of Port du Guildo on 15 October 2008 at 17:25:08 - White egret taking off with the tidal bore front arrival - File: Arguen046.jpg, Shutter speed: 1/320 s

Fig. 4-8 - Tidal bore of the Arguenon River in the Port du Guildo on 15 October 2008 at 17:32:01 - Seagulls taking off at the bore arrival - Note the darker colour of the waters next to the bank (far left) - File: Arguen108.jpg, Shutter speed: 1/100 s

(A) Advancing tidal bore at 17:32:20 - Note the bore advancing on a dry sand bank on the right of the photograph - File: Arguen119.jpg, Shutter speed: 1/100 s

(B) Advancing tidal bore 12 seconds later (at 17:32:32) - File: Arguen126.jpg, Shutter speed: 1/125 s

Fig. 4-9 - Tidal bore of the Arguenon River in the Port du Guildo on 15 October 2008, immediately downstream of Pont du Guildo

Fig. 4-10 - Details of the tidal bore of the Arguenon River between Le Guildo and Créhen on 15 October 2008 at 18:04 - The bore celerity was about 1.1 m/s - View from the GR34 footpath on the left bank - File: Arguen166.jpg, Shutter speed: 1/125 s

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He further acknowledges the support of his family, his wife Ya-Hui CHOU and his children Bernard CHANSON, Nicole CHANSON and André CHANSON who "chased" tidal bores and *mascarets* with him.

Appendix A - Maps of tidal bore affected estuaries in France

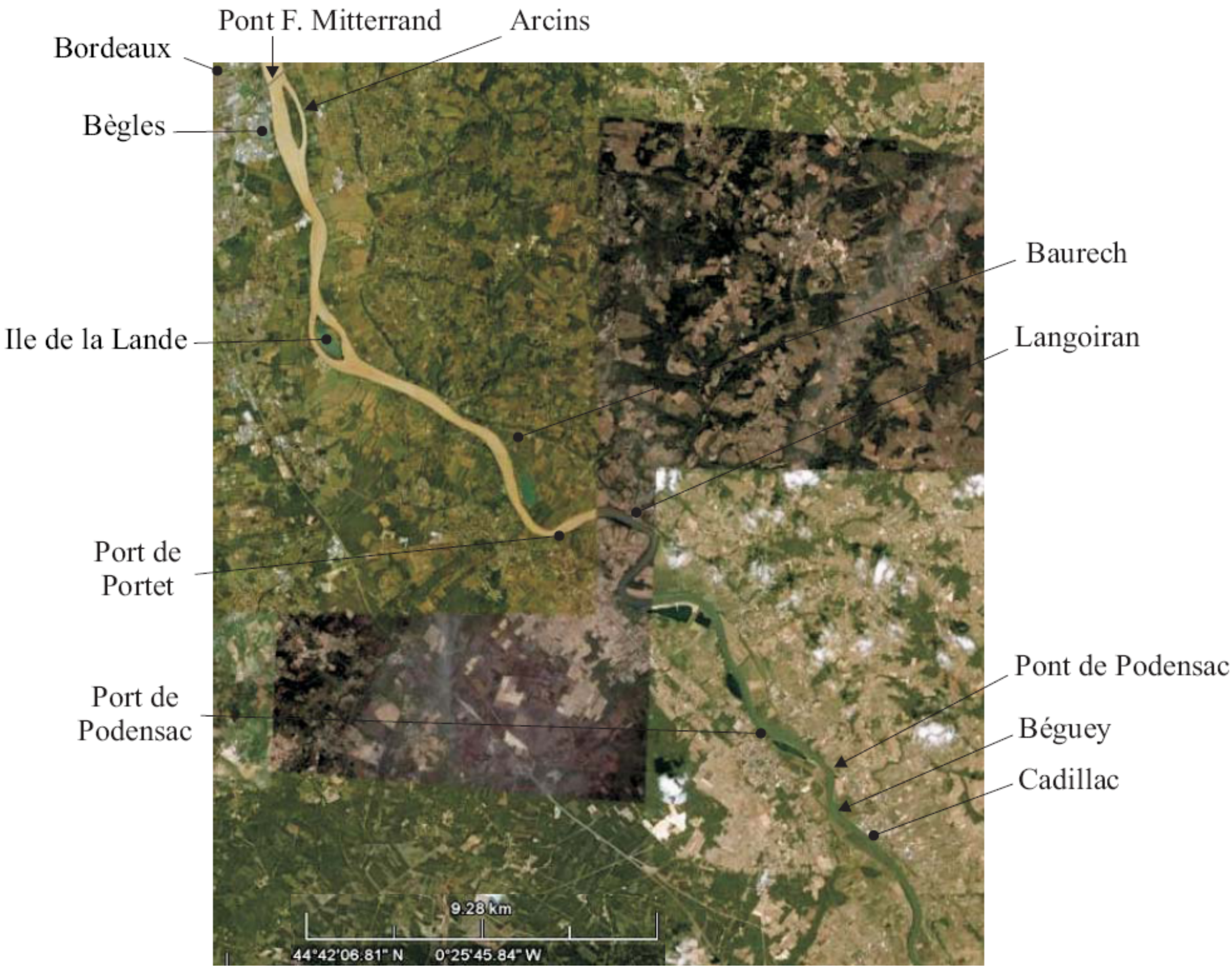
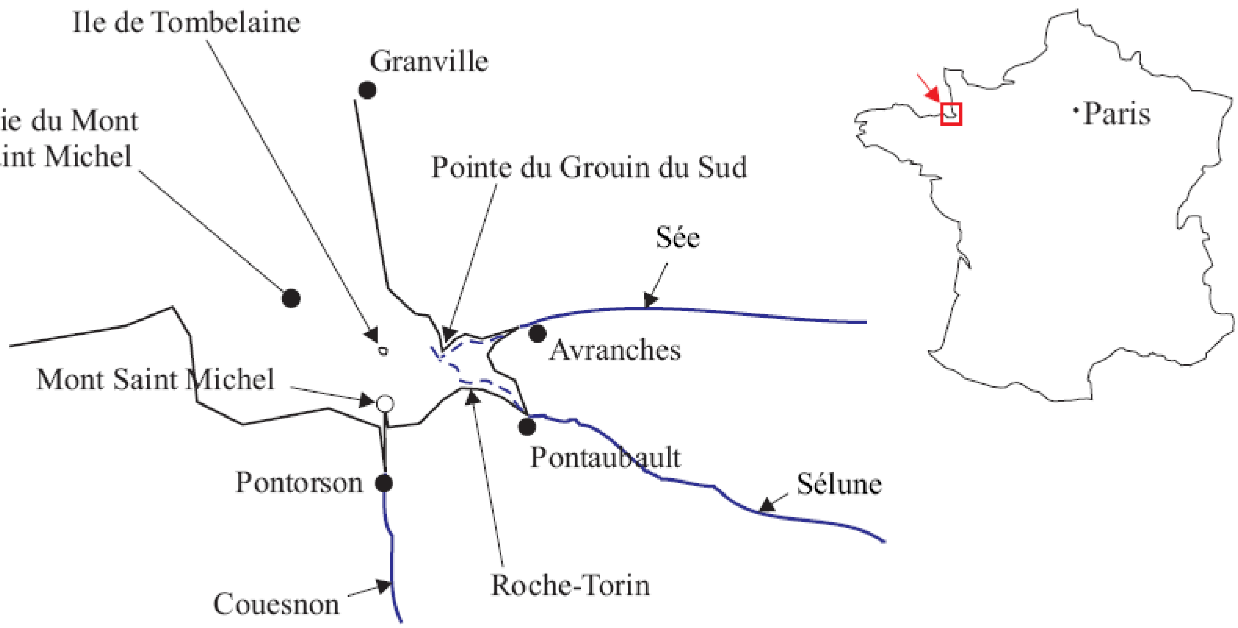


Fig. A-1 - Aerial photograph of the Garonne River estuarine zone between Bordeaux and Cadillac (Google Earth™ on 29 Sept. 2008)

Fig. A-2 - Aerial photograph of the Dordogne River estuarine zone between Cubzac-les-Ponts and Libourne (Google Earth™ on 30 Sept. 2008)



(A) Map of the Baie du Mont Saint Michel and its main rivers : the Sélune, Sée and Couesnon Rivers

Fig. A-3 - Baie du Mont Saint Michel

(B) Aerial photograph of the Baie du Mont Saint Michel (Google Earth™ on 3 Oct. 2008)

Fig. A-3 - Baie du Mont Saint Michel

Fig. A-4 - Aerial photograph of the Baie de la Frênaye and Baie de l'Arguenon, Brittany (Google Earth™ on 17 Oct. 2008)

Appendix B - Digital files and slide show movie

A short slide show movie was produced from the tidal bore photographs shown in the report. The sound tracks are the audio recording of the tidal bore of the Sée River and of the ensuing whelps on 15 October 2008 at the Pointe du Grouin du Sud, Vains (France) (App. C). Details of the movie and audio files are given below including the filenames, file format, and a description of the contents. The captions of each photograph is given in sections 2, 3 and 4.

The movie file and audio track files are deposited with the digital record of the publication at the institutional open access repository of the University of Queensland: {http://espace.library.uq.edu.au/}. They are listed as part of the technical report deposit at {http://espace.library.uq.edu.au/list/author_id/193/}.

Filename	Format	Description
Mascaret08.wmv	Windows Media WMV	Slide show made from photographs of tidal bores in France taken by Hubert CHANSON. The movie and all photographs are Copyrights Hubert CHANSON 2008. Duration: 7'46".
See01.wav	Waveform audio format WAV	Audio recording of the tidal bore of the Sée River at Pointe du Grouin du Sud on 15 October 2008 between 06:48 and 06:52. The audio recordings are Copyrights Hubert CHANSON 2008. Duration: 3'41".
SeeWhelps01.wav	Waveform audio format WAV	Audio recording of the tidal bore whelps of the Sée River and of the flood tide flow at Pointe du Grouin du Sud on 15 October 2008 between 06:53 and 06:55. The audio recordings are Copyrights Hubert CHANSON 2008. Duration: 1'18".

The movies files of Appendix B are available in the institutional open access repository of the University of Queensland (Brisbane, Australia) and are deposited at UQeSpace {http://espace.library.uq.edu.au/}. The Digital Files are a WMV movie and WAV audio files. The deposited files were converted to Flash video for video streaming.

At request, the writer may provide the Windows Media WMV movie and WAV audio files as a single compressed file (Filename Mascaret08.7z). The file was prepared with 7-zip version 4.23. The software 7-zip is an open source software. Most of the source code is under the GNU LGPL license. The unRAR code is under a mixed license: GNU LGPL + unRAR restrictions. The software 7-zip may be freely downloaded from {www.7-zip.org}.

The copyrights of the movie, all photographs and the audio recordings are the sole property of Hubert CHANSON. Any use of the movie, photographs and audio files available in the digital appendix must acknowledge and cite the present report:

CHANSON, H. (2008). "Photographic Observations of Tidal Bores (Mascarets) in France." *Hydraulic Model Report No. CH71/08*, Div. of Civil Engineering, The University of Queensland, Brisbane, Australia, 104

pages, 1 movie and 2 audio files (ISBN 9781864999303).

Further details on the report including the digital appendix may be obtained from Prof. Hubert CHANSON {h.chanson@uq.edu.au}.

Appendix C - Sound recording of a tidal bore event

C.1 Presentation

The sounds generated by a tidal bore combine noises caused by the turbulence in the bore front and whelps, entrained air bubbles in the bore roller ('white waters'), sediment scour beneath the bore front, of the banks and on the sand banks, and the impacts on obstacles (rocks, bridge piers).

A tidal bore is a powerful and "noisy" process. In China, the noise of the Qiantang River bore was compared to "the clamor of a hundred thousand troops" in a poem by LI Guo of the Tang dynasty ([1]) and to "10,000 horses break out of an encirclement, crushing the heavenly drum, while 56 huge legendary turtles turn over, collapsing a snow mountain" by the Chinese poet QIU Yuan (1247-1326) during the Yuan Dynasty (DAI and ZHOU 1987). The sounds generated by a tidal bore were also called a "great destructive noise", and compared to the sound of locomotive train, of bass drums, of thunder and of torrent.

Tidal bores can be heard from far away. During his expedition in the Qiantang River mouth on 20 September 1888, Captain MOORE heard the first murmur of the bore one hour before it reached its Pandora ship (MOORE 1888, p. 7). In the Baie du Mont Saint Michel, the writer heard often the tidal bore 25 to 30 minutes before the bore front reached him. Animals can be more sensitive to the tidal bore sounds than the human ear (Table C-1). But when the bore closes in, the rumbling noise may disorientate some. In the Baie du Mont Saint Michel, sheep (*moutons de prés salés*) have been outrun and drowned by the tidal bore. In Alaska, moose have tried unsuccessfully to outrun the bore (MOLCHAN and DOUTHIT 1998). In each case, the animals were panicked with the deafening noise of the bore, losing their directional senses, although they could run faster than the bore front.

A Canadian composer, Gordon MONAHAN, created a musical piece that was a metaphorical interpretation of the tidal bore action, using sound recordings of water flow from the Bay of Fundy: "the tidal bore of the Maccan River" (MONAHAN 1981).

Herein, the sounds generated by a tidal bore event were measured and the acoustic characteristics were analysed. The present work takes preliminary steps towards an acoustic signature technique for characterizing the tidal bore process.

C.2 Field measurements

The sounds were recorded with a digital video camcorder Canon MV500i equipped with a stereo electret condenser microphone. The audio signal (PCM digital sound: 16 bit, 48 kHz/2 channels) was separated from the video signal and the WAV file is available in Appendix B.

On 15 October 2008, the tidal bore of the Sée-Sélune River system was observed at the Pointe du Grouin du Sud in the Baie du Mont Saint Michel during the early morning. The video camera and microphone were placed on the rocky promontory (Fig. C-1) and the microphone was facing the tidal bore front for the whole duration of the record. Figures C-1 and C-2 present the promontory while a map is shown in Appendix A.

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[1] Tang dynasty period: 618-907 AD. Yuan dynasty period: 1206-1368 AD.

A miniDV tape recorder digitized the signal at 32 kHz, implying an alias frequency of about 16 kHz. The range of tidal bore conditions caused a difference in acoustic signal power of up to 20 dB corresponding to a factor of 10 in sound intensity during the record. Since all data recorded on tape should have similar magnitudes to minimise distortion or loss of dynamic range, the entire record was sub-divided into three periods of comparable sound intensity to deliver comparable recorded quality during the signal processing. The WAV recordings were processed with the software DPlot™ version 2.2.1.6. Fast Fourier transforms (FFTs) were taken. Each experimental dataset was sub-sampled into sub-sets 2 s long to give a frequency span of 0-16 kHz.

Table C-1 - Frequency hearing range of various species

Species (1)	Approximate frequency range (Hz) (2)
Young human ear	20 to 20,000
Cat	45-64,000
Cow	23-35,000
Dog	67-45,000
Horse	55-33,500
Sheep	100-30,000
Rabbit	360-42,000
Beluga whale	1,000-123,000
Catfish	50-4,000
Elephant	16-12,000
Porpoise	75-150,000
Tuna	50-1,100
Chicken	125-2,000
Cockatiel	250-8,000
Owl	200-12,000

References: WARFIELD (1973), FAY (1988), Encyclopædia Britannica (2008).

Fig. C-1 - Panoramic view of the Baie du Mont Saint Michel seen from the Pointe du Grouin du Sud on 19 October 2008 at 08:20 at sunrise and low tide - Note the rocky promontory of Pointe du Grouin du Sud in the foreground, the Mont Saint Michel and Ile de Tombelaine in the background, and the joint Sée-Sélune River system on the right of the photograph - File: See283.jpg

Fig. C-2 - Photograph of the tidal bore of the Sée River (foregound) reaching the Pointe du Grouin du Sud on 19 October 2008 at 09:31 - Note the rocky promontory in the foreground, the Mont Saint Michel in the background, and the interactions between the tidal bore flow and the rocks in the foreground - File: See345.jpg, Shutter speed: 1/1,000 s

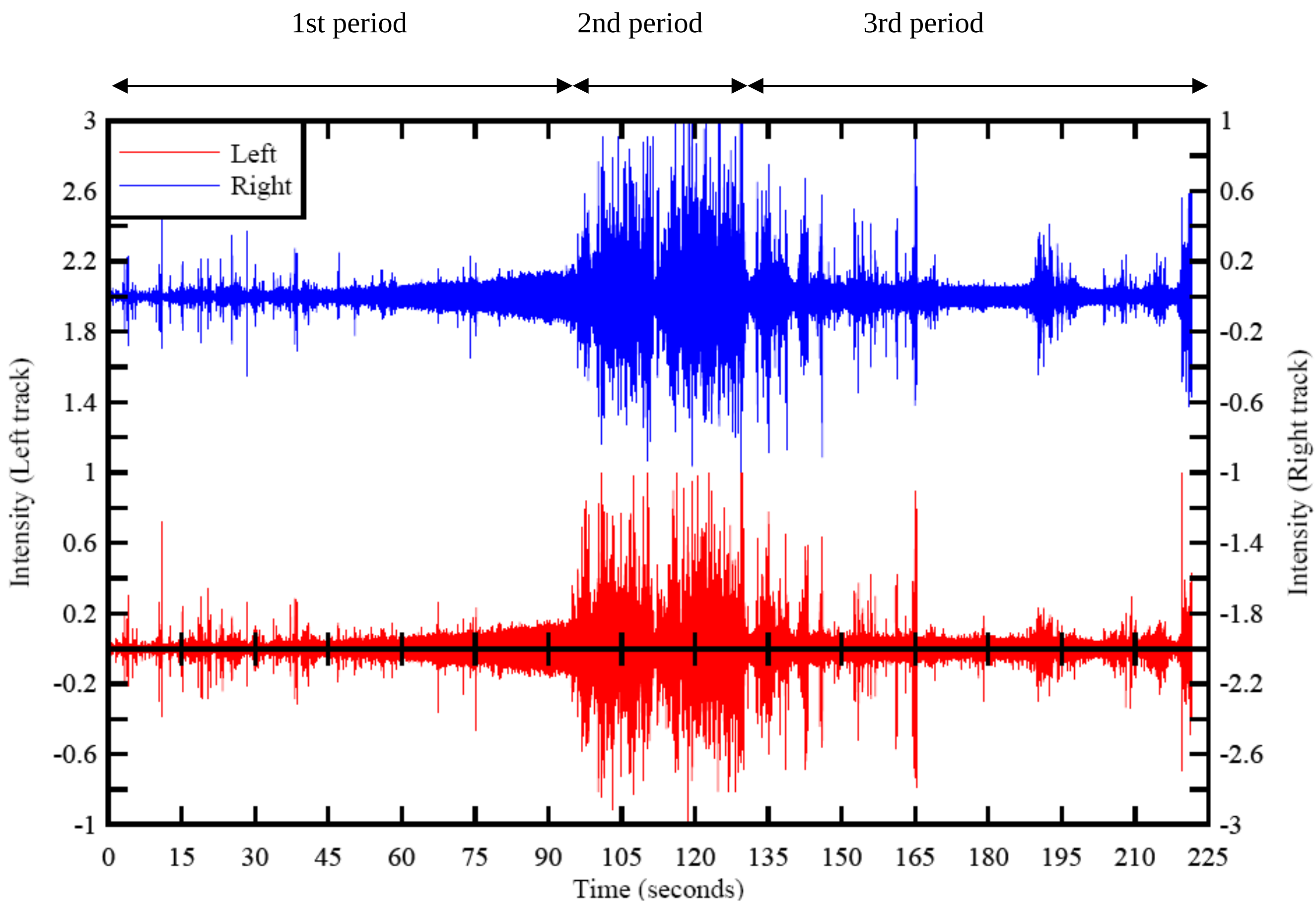

Fig. C-3 - Audio signal the tidal bore of the Sée River at Pointe du Grouin du Sud on 15 October 2008 between 06:48 and 06:52

C.3 Field observations

The tidal bore (*mascaret*) was seen in the morning darkness ([2]). The tidal bore came from the Sée-Sélune River channel (Fig. C-1 right). The bore front passed the rocky promontory of the Pointe du Grouin du Sud at 06:50, and entered into the Sée River channel while another tidal bore continued into the Sélune River channel towards Roche-Torin (Fig. C-1 left). The entire process was a breaking bore, similar to the one seen in Figures 3-15 to 3-17 which were taken 12 hours earlier. The white waters of the breaking bore were clearly seen with a torch.

The sound measurements started at 06:48 and lasted for about 4 minutes. The tidal bore passed in front of the promontory at 06:50. The entire bore event may be sub-divided into three consecutive periods (Fig. C-3). From the first 95 seconds of the record, the tidal bore approached Roche-Torin and the sound intensity gradually increased. For $95 < t < 130$ s, the tidal bore reached the rocky promontory and "crashed" onto the rock formations, yielding loud and powerful noises. The tidal bore was just in front of the promontory, as seen as in Figure C-2, for $t = 100$ to 102 s ([3]). For $130 < t < 221$ s, the tidal bore continued into the Sée River channel towards Avranches and the Sélune River channel towards Roche Torin respectively. During this

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[2] While it was a full moon, the sky was cloudy and there were intermittent showers in the early morning.

[3] Visual observations with a torch.

third period, the audio record was a combination of the sounds generated by the tidal bore in the Sée River channel (foreground), the flood tidal flow past the rocky promontory of Pointe du Grouin du Sud and the tidal bore in the Sélune River channel (background) (Fig. C-1).

The entire sound record is presented in Figure C-3 and the three distinct periods are highlighted.

The acoustic properties of the record were analysed in terms of the absolute value (or modulus) of the sound intensity. Typical results are summarised in Table C-2 (columns 5 and 6), showing the mean and standard deviation of the intensity modulus. It is seen that the noises during the second period, when the tidal bore passed around the rocky promontory, was in average 5 times more powerful than during the first period (incoming bore). The quantitative data were supported by the personal observations during the tidal bore event. The ratio of the standard deviation to mean absolute value was typically between 1.1 and 1.5 for the complete study.

A spectral analysis was further conducted, and basic properties are summarised in Table C-2 (columns 7 and 8). The acoustic spectra are shown in Figure C-4 for the sound record shown in Figure C-3 and for each period. Each spectrum shows a minimum in energy below 5 Hz, indicating that the low-frequency rumbling noise of the tidal bore noise is above 5 Hz, within the entire audible range of sounds for a human ear ([4]). In each spectrum, a dominant frequency was observed and the characteristic values are summarised in Table C-2 (column 7). The dominant frequency was a low pitch, or rumble, with values between 74 and 131 Hz depending upon the period (Table C-2).

During the first period, the tidal bore was a breaking bore advancing in the main channel and over sand banks and mudflats. The low-frequency sound (76-77 Hz) might be considered to be a characteristic feature of an advancing roller. For the second period, the tidal bore impacted onto the rocky promontory and the impact was an energetic process generating louder noises of a higher pitch yielding a dominant frequency around 113-131 Hz. This is clearly seen in Figure C-4 where the higher acoustic energy illustrates a louder noise, as well as by the integral of the power spectral density (PSD) function (Table C-2, column 8). During the third period, the sounds were a combination of the tidal bores leaving the Pointe du Grouin du Sud in the Sée and Sélune River channels, as well as the impact of the flood flow on the promontory rocks. This yielded a slightly flatter, broader acoustic spectrum (Fig. C-4). Note that, since all peak frequencies were greater than the low-frequency noise found below 5 Hz, no high-pass filtering was required.

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[4] The entire audible range of sounds extends from about 20 to 20,000 Hz for normal young ears (Encyclopædia Britannica 2008).

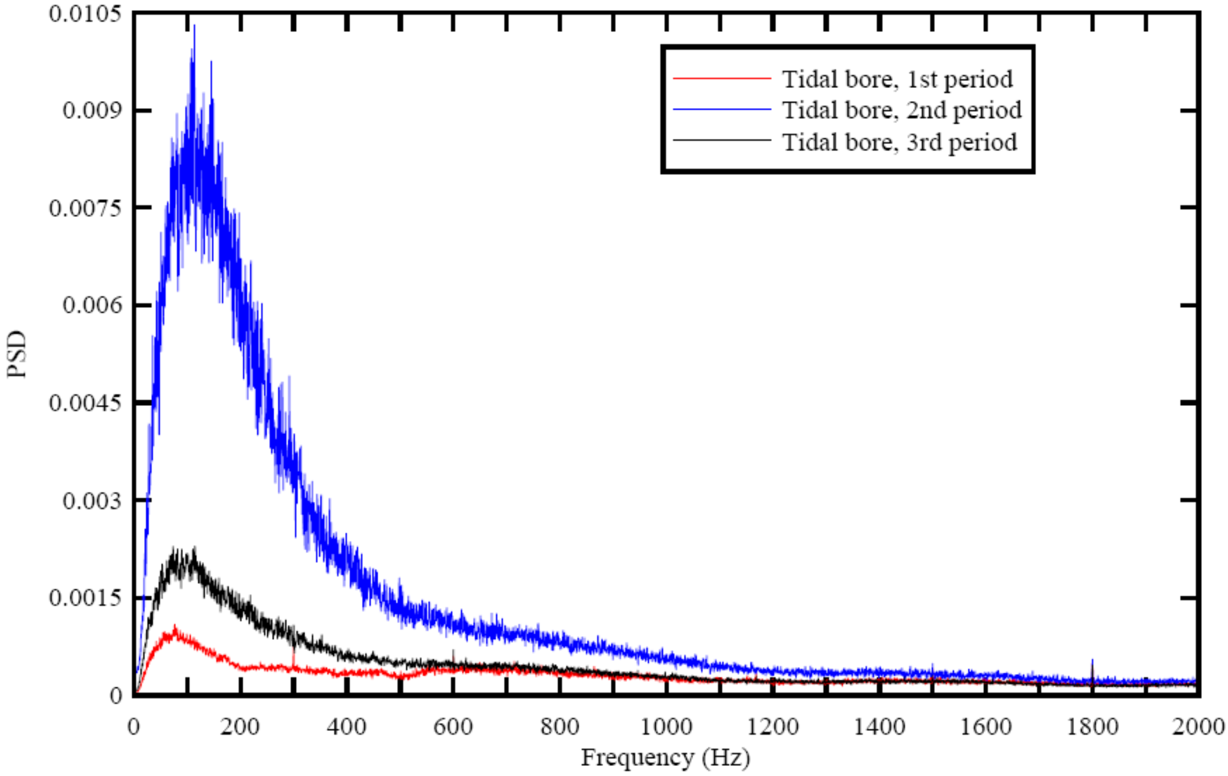

Fig. C-4 - Acoustic spectra of the tidal bore event, Sée River at Pointe du Grouin du Sud, Baie du Mont Saint Michel on 15 October 2008 between 06:48 and 06:52 - Average of left and right sound track spectra

C.4 Discussion

The acoustic signature of the tidal bore event was compared with two other sound records (Table C-2). One was the sound of the tidal bore whelps and flood flow at the Pointe du Grouin du Sud about 3 to 5 minutes after the tidal bore passage at Pointe du Grouin du Sud. The data were recorded with the same microphone and at the same location as the tidal bore event, but the microphone was facing the Pointe du Grouin du Sud for the entire recording. During this record, the sounds were a combination of the noises of the flood flow crashing on the rocks of the promontory, of the flood flow in the Sée River channel just below the Pointe du Grouin du Sud ([5]), and of the tidal bores in the Sée and Sélune River channels ([6]). The sounds were powerful and quite violent.

The second record was taken from the left bank of the Dordogne River at Port de Saint Pardon on the 18 October 2005 during the passage of an undular tidal bore. The microphone was located in the vicinity of a jetty, and it was fixed for the duration of the record. That data set is presented in Figure C-5. The first period corresponded to the arrival of the tidal bore towards Port de Saint Pardon while the second period was dominated by the successive breaking of the undulations on the jetty during and after the bore passage ([7]). The characteristics of these two records are reported in Table C-2.

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[5] See the Sée River channel South of and just below the Pointe du Grouin du Sud in Figures 3-17 and 3-20.

[6] See the Sée and Sélune River channels in Figures 3-21 and 3-6 respectively.

[7] See the breaking of the Dordogne River tidal bore undulations on the jetty in Figures 2-15, 2-17, and 2-18.

The acoustic spectrum of the whelps and flood flow at Pointe du Grouin du Sud is also shown in Figure C-6 where it is compared with the tidal bore event data. In Figure C-6, both horizontal and vertical axes have a logarithmic scale. The plots highlight a minimum in energy at roughly 1 to 5 Hz, as well as maxima for frequencies between 76 and 131 Hz. While all data sets corresponded to low-frequency noises, the loudness of the tidal bore impact on the rocky promontory of Pointe du Grouin du Sud is highlighted by its high acoustic energy (Fig. C-6, Tidal bore 2nd period), while the second loudest sound record was that of the whelps and flood flow (Fig. C-6).

The Dordogne and Sée River tidal bores exhibited similar acoustic features during the first period of each record (Fig. C-3 and C-5). That is, an increasing sound level with increasing time, as well as a sound intensity much lower than during the subsequent record sections. The acoustic spectra of the Sée River and Dordogne River tidal bores showed a low-pitch dominant frequency, although the Dordogne River tidal bore event presented a higher dominant frequency (191 to 233 Hz) than that of the Sée River tidal bore (Table C-2, column 7). There were however some key differences between the two tidal bore events. First the Sée River tidal bore was a breaking bore with a well-defined roller, while the Dordogne River tidal bore was an undular bore. The turbulence and air bubble entrainment in the bore roller generated lower frequency rumble sounds. Second, the Dordogne River tidal bore record incorporated some background noises including voices and noises generated on the river bank, and the microphone was fixed for the entire duration.

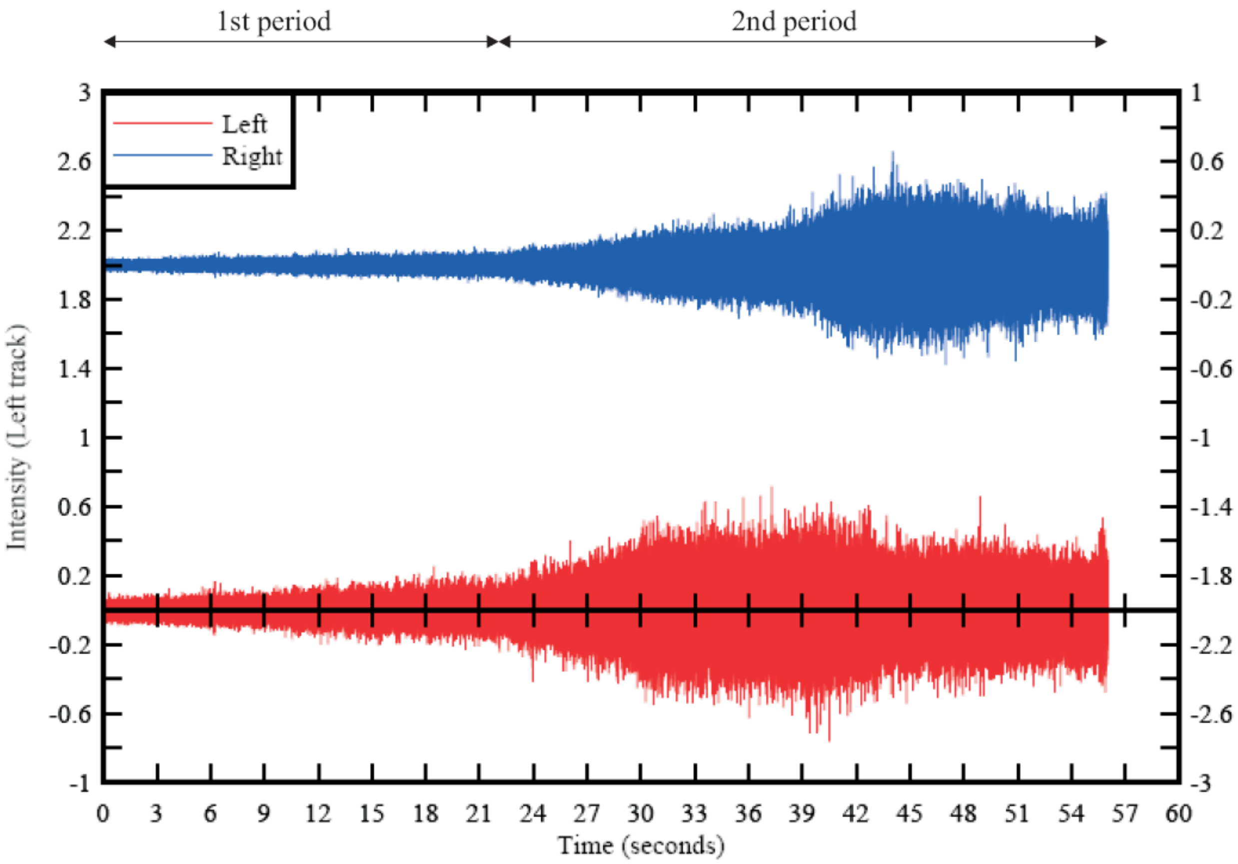

Fig. C-5 - Audio signal the tidal bore of the Dordogne River at Port de Saint Pardon on 18 October 2005 (Courtesy of Patrick VIALLE)

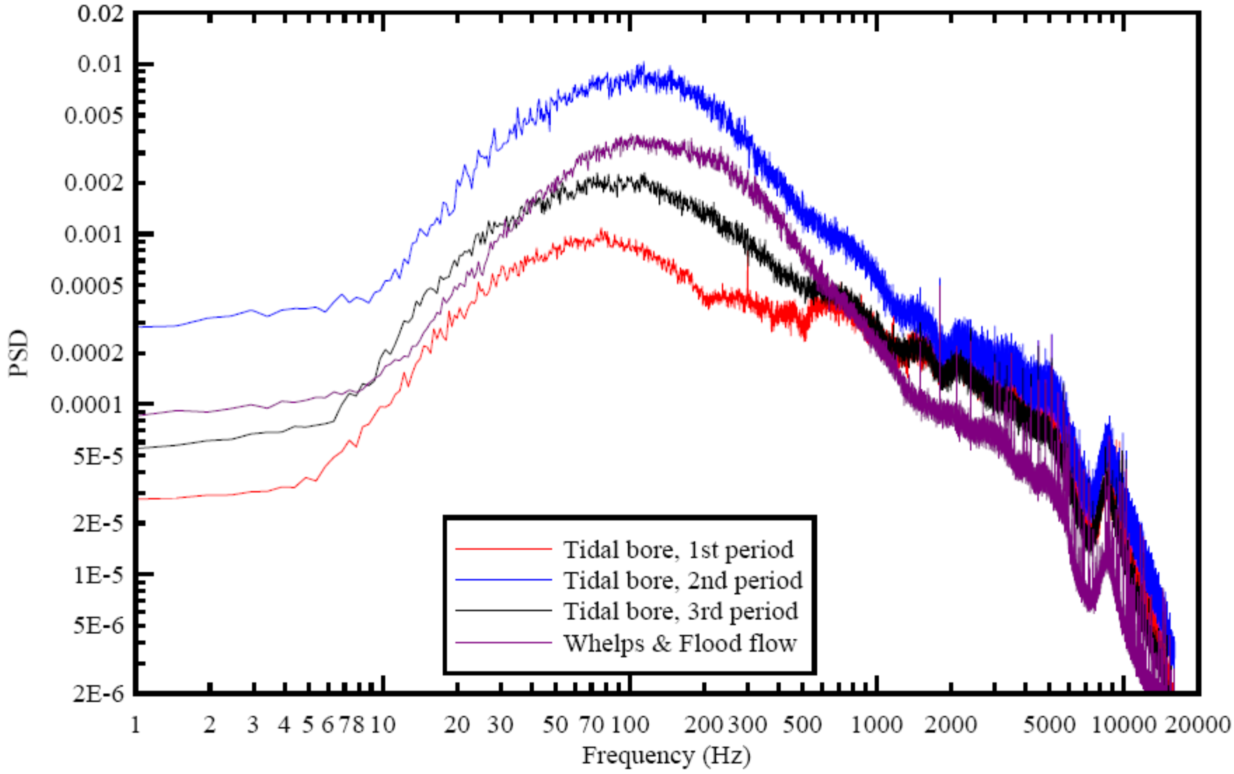

Fig. C-6 - Comparison in acoustic spectra between the tidal bore (06:48 to 06:52), and its whelps and flood flow (06:53 to 06:55), at Pointe du Grouin du Sud, Baie du Mont Saint Michel on 15 October 2008 - Average of left and right sound track spectra

Table C-2 - Acoustic properties of tidal bore sound record

Reference (1)	Record (2)	Duration (s) (3)	Track (4)	Average sound intensity modulus (5)	Std sound intensity modulus (6)	Dominant frequency (Hz) (7)	Integral of PSD function 0-16 kHz	Remarks (9)
Sée River tidal bore, 15 Oct. 2008	**Tidal bore (breaking)**							From Pointe du Grouin du Sud (right bank)
	1st period	95	Left	0.0159	0.0178	76.2	1.234	Incoming tidal bore
			Right	0.0143	0.0160	76.7	1.181	
	2nd period	35	Left	0.0786	0.0851	130.9	3.625	
			Right	0.0840	0.0920	113.3	3.858	
	3rd period	91	Left	0.0230	0.0326	92.3	1.356	Bore, whelps and flood flow
			Right	0.0249	0.0379	73.8	1.501	
	Whelps							From Pointe du Grouin du Sud,
	Entire record	78	Left	0.0455	0.0502	125.45	1.663	3 to 5 min. after bore passage
			Right	0.0414	0.0392	89.4	1.485	
Dordogne River, 18 Oct. 2005	**Tidal bore (undular)**							From Port de Saint Pardon (left bank)
	1st period	22	Left	0.0328	0.0275	191.4	1.611	Incoming tidal bore
			Right	0.0141	0.0113	233.4	0.800	
	2nd period	44	Left	0.0988	0.0789	*224.5*	--	Bore passage in front of jetty
			Right	0.0676	0.0624	*241.0*	--	

Notes: Dordogne River data set provided by Patrick VIALLE; Std = standard deviation; *Italic*: data analysis without sub-sampling.

C.5 Summary and conclusion

The sound record of a tidal bore event showed that there were two to three distinct periods. These were (a) the incoming tidal bore when the sound intensity increased with the approaching bore front, (b) the passage of tidal bore in front of the microphone where the impacts of the bore on the bank, rocks or jetty generated powerful noises, and (c) the upstream propagation of the bore when the flood flow motion caused additional loud noises. These periods were visually observable and heard on site. Further the data highlighted the loud noises generated during the whelps and flood flow shortly (a few minutes) after the tidal bore passage.

During the first period, the sounds generated by the incoming bore were likely dominated by the bore front hydrodynamic processes including turbulence, air entrainment, breaking next to the banks and sediment scour. A comparison between two tidal bore events illustrated both common features and differences. In each case, the approaching tidal bore generated an increasing sound level with increasing time, although the sound levels were much lower than during the subsequent record sections. Both tidal event events generated low-pitch sounds. For a breaking bore process, however, the audio record gave a lower pitch sound (76-77 Hz) than during the undular bore event (191 to 233 Hz). The low pitch was comparable with the dominant frequency of bass drums and locomotive trains (Table C-3) and the result explained the analogy with the sound generated by breaking bores (e.g. Qiantang River, Sée and Sélune Rivers). It is likely the difference in dominant sound frequencies resulted from some fundamental hydrodynamic differences between undular and breaking bores (KOCH and CHANSON 2008a, CHANSON 2008b).

Table C-3 - Comparison of dominant sound frequencies generated by tidal bores, locomotive trains and music instruments

Type (1)	Sub-type (2)	Dominant frequency(ies) (Hz) (3)	Remarks (4)
Approaching tidal bores	Breaking bore	76-77	Sée River tidal bore, 15 Oct. 2008
	Undular bore	191-233	Dordogne River, 18 Oct. 2005
Locomotive train	3000 Hp diesel locomotive	60	Measured at the engineer's ear in the cabin (MAGUIRE 2004).
	Locomotive whistle	~ 400	
Drums	Concert bass	40-100	
	Kettle	8-150	
Piano	A0	27.5	Fundamental frequency.
	A1	55	
	Middle C	246	
	A4	440	

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